AFRL-OSR-VA-TR-2015-0008

An Incentivized Capstone Design Team Applying the Systems Engineering Process

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01/02/2015
Final Report

DISTRIBUTION A: Distribution approved for public release.

Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/ RTB
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* 29-12-2014	**2. REPORT TYPE** Final Performance	**3. DATES COVERED** *(From - To)* August 2011 - August 2014

4. TITLE AND SUBTITLE An Incentivized Capstone Design Team Applying the System Engineering Process	**5a. CONTRACT NUMBER** **5b. GRANT NUMBER** FA9550-11-1-0234 **5c. PROGRAM ELEMENT NUMBER**
6. AUTHOR(S) Beale, David, G.	**5d. PROJECT NUMBER** **5e. TASK NUMBER** **5f. WORK UNIT NUMBER**
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Auburn University	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)** **11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

12. DISTRIBUTION / AVAILABILITY STATEMENT

Distribution A

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Auburn University senior project students have competed annually in three of the university engineering design challenges, these included the portable ascent device in 2012, the portable spanning device in 2013 and the heavy lift competition in 2014. Students submitted reports, made presentations to military personnel and demonstrated their device each year as part of the competition. The portable ascent device was a ladder that the soldier attach to the wall and used to incrementally climb the wall, a ladder length at a time, but failed due to a poorly welded bracket at the competition. The portable spanning device was a bridge with handrails that was made from composite tubing that fit in a soldiers backpack, and successfully spanned 16' at the competition. The heavy lift device was an inflatable bag concept that successfully lifted approximately 26,000 lb and won the 2014 competition.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)*

Spring 2012

USAF Research Lab

Portable Ascent Device

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Corp 8

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ABSTRACT:

The mission objective of this senior design project is to produce a mechanism that will quickly and effectively transport Airmen over obstacles 90 ft. tall or less. This project is being organized as part of an Air Force sponsored competition. The device must be able to be carried and implemented by a squad of Airmen, safely support the weight of an Airman and gear, allow for a climbing speed of 45 ft./min., weigh less than 5 lbs., and take up less than 1 ft.^{3}. These and other target goals will be tested in a competition at Calamityville in Fairborn, OH during the week of April 16, 2012.

This project began by creating multiple designs and evaluating them using a house of quality. The best design presented was that of a device to help a climber attach anchor points at longer intervals. The device will work by bolting to the wall and allowing the Airman to scale 9 ft. easily. At the top of the device the Airman will install another anchor point and raise the device to that anchor point. The Airman will then repeat the steps until the top is reached. The device increases the climbing speed by making the anchoring process more efficient. Once the first Airman reaches the top of the obstacle he will install a fixed line and the remaining Airmen will use a powered ascender to climb the rope. The original design has been continuously refined and is now optimized to meet the goals of the project.

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1.0 Introduction:

The Air Force Research Lab's annual design competition's purpose is to promote and sustain university research and education focused on innovative military systems. Objectives and design constraints differ each year and are specified by the AFRL management team. An organized competition amongst undergraduate teams is held at the end of the academic year to determine the best design. The purpose of the competition setting is to provide students with enhanced incentives for exemplary performance. Winners of the competition will be encouraged to apply for additional funded projects.

The methods used to solve the problem established by the AFRL management team demonstrate the students' knowledge of the systems engineering process. The portions of this process covered in this report include the steps related to validation and verification. Included are detailed descriptions of steps taken to pinpoint problems associated with sub-systems, corrective actions taken to alleviate the problems, and the resulting improvements to the design. Details on the risks associated with the operation of the device are also detailed to point out any potential dangers that would require attention.

2.0 Mission Objective:

The mission objective of this project is to create a portable device that allows Airmen to scale obstacles up to 90 ft. the device should also be safe to operate, minimize time spent climbing, lightweight, and environmentally adaptable. The target goals are for the final design to weigh less than 5 lbs., take up less than 1 $ft.^3$ of space, and ascend at a rate of 45 ft./min. Along with these

design goals, it is the groups' goal to win the Air Force competition at Calamityville in Fairborn, OH during the week of April 16, 2012. It is also important to note that the weight, size, and speed requirements are strictly for scoring criteria and the Air Force will not disqualify an entry that does not meet them.

3.0 Architectural Design Development:

3.1 Product Hierarchy:

The Portable ascent device has four subsystems: main structure, wall plate, coupling and pivot, and the secondary ascent for the remaining Airmen. The list below shows the product hierarchy of the final design and also includes a section for accessories that are not specific to one subsystem.

Product Hierarchy

- Portable Ascent Device
    - Main Structure – 1
        - 3-foot Braided Carbon Fiber Tube, 2" dia. – 2
        - Aluminum Hinge – 1
        - 3/8" Push Button Pin – 2
        - Shaft Collar – 4
        - Protective Rubber Strip – 4
        - Threaded Foot Peg – 6
        - Aluminum End Sleeve – 1
        - Eye Bolt – 1
    - Coupling and Pivot – 1

        - Aluminum Coupling – 1
        - Detent Plate – 2
        - 1” x 1” AL Bar – 1
        - 3/8-16 Pivot Bolt – 2
        - 3/8-16 Nut – 2
        - Threaded Reinforcement Rod – 1
        - 3/8” Push Button Pin – 1
        - 1/4" Push Button Pin – 1
    - Wall Plate – Mission Specific
        - Plate – 1
        - Square Tube – 1
        - Screw – 1
        - Hoist – 1
    - Fast Ascender - 1
        - Atlas Device – 1
- Accessories
    - Rotary Hammer Drill – 1
    - Wall Plate Expansion Bolt - Mission Specific
    - Climbing Harness – 1
    - Quick Draw Carabiner – 1
    - Static Climbing Rope – Mission Specific Length
    - Wall Plate Bolt Hole Aligner – 1
    - Rope Aider – 1

3.2 Wall Plate Sub-Assembly:

For detailed CAD drawings please see appendix.

Purpose:

The wall plate supports the main structure connecting it to the climbing surface (**Error! Reference source not found.**). It also provides a temporary anchor to support the operator while articulating the device.

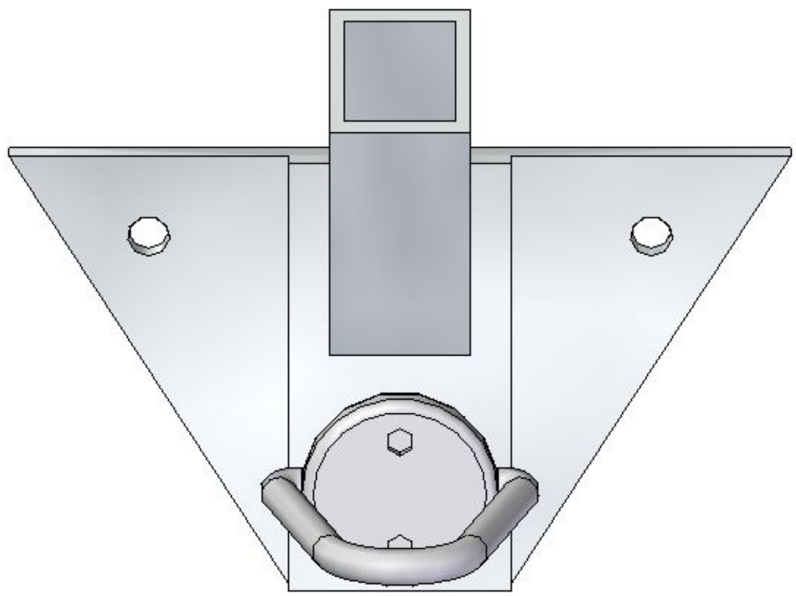


Figure 1 - Front View of Wall Plate

Design Requirements:

- Securely support the main structure.
- Do not obstruct access to drilling points.
- Provide a temporary anchor location for the operator.
- Minimize weight (Less than 2.0 lb.).
- Minimize volume.

Current Design:

The proposed design is a wall plate consisting of an angled plate with a square tube extending off at a 45º angle (**Error! Reference source not found.** and 3). A hoist ring is mounted below the square tube to provide a temporary anchor for the operator while articulating the device. On either side of the tube, there is a 13/32” diameter hole. These holes will be used in conjunction with two 3/8” expansion bolts to secure the wall plate to the climbing surface.

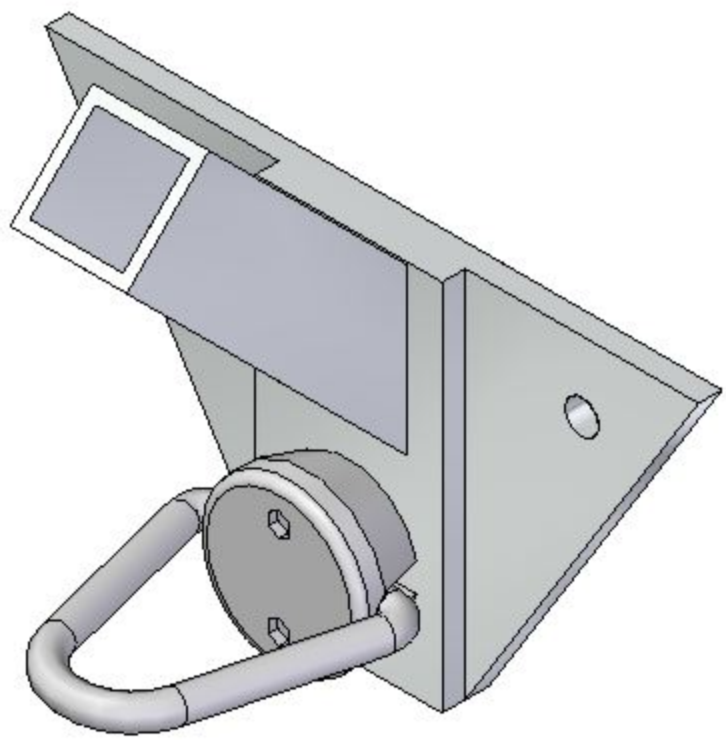


Figure 2 - Isometric View of Wall Plate

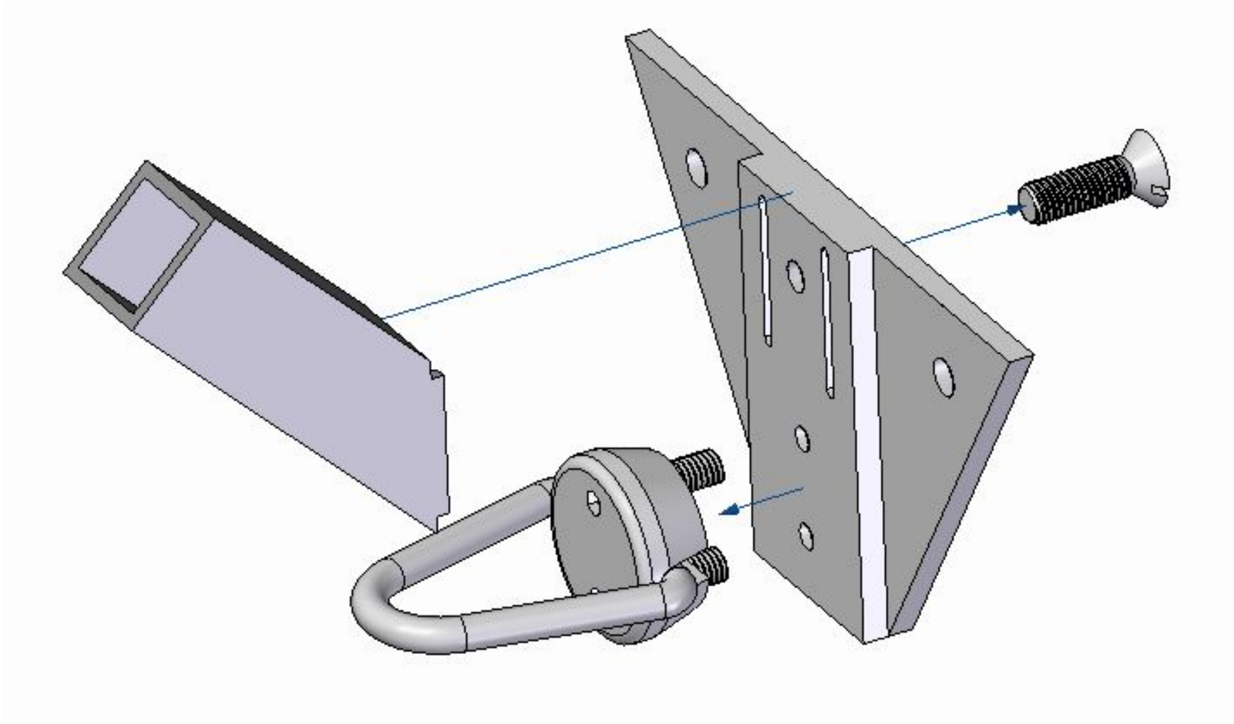


Figure 3 - Exploded View of Wall Plate

The proposed wall plate is relatively compact. The plate is 7” wide at the top and 2” wide at the bottom. The overall height of the plate is 4”. The main structure would be inserted into the square 2.5” tube. With this design the wall plate’s projected weight is 1.5 lbs.

During operation, holes will be drilled into the climbing surface. Next, climbing-grade expansion bolts will be placed to secure the wall plate to the surface. The wall plate will be placed over these bolts and secured with two nuts. Once secured, the operator will secure themselves to the hoist ring using quick draws. They will then insert lift the main structure up to the wall plate and insert the 1” x 1” bar from the coupling into the square tube. Once inserted into the wall plate, the main structure will be fixed in the upright position. This will allow the

operator to disconnect from the wall plate climb to the top, rotate the device and repeat the process.

Design Changes:

Since the last review, a prototype of the wall plate was manufactured and assembled. During this process, several modifications were made to the wall plate to ensure a better fit and easier manufacturability. The mounting holes were increased from 3/8” to 13/32” diameter to allow for more clearance and easier insertion of the climbing anchors. The slots that prevent rotation were extended to the top of the plate for easier manufacturing. The hole for the counter-sunk screw was converted from a threaded hole to a thru hole to prevent thread misalignment at the plate plug interface. Finally the tube was welded to the plate to further strengthen the connection.

Design Considerations:

The plate in the proposed design is engineered to save weight. Instead of making the wall plates a square, the excess material has been removed, which created two angled wings. Each wing encompasses a mounting point while allowing the holes to be 1.5 times their diameter away from the edges. Additionally, since there are no threaded holes in the wings, there is no need for this section to be as thick as the rest of the Wall plate. Therefore, each wing is ¼” instead of ½” thick.

With early revisions of this design, there was a concern that the tube would rotate relative to the plate. To prevent this from occurring, the tube is welded and tabs are milled into the end of the square tube. These tabs fit into

grooves milled into the plate. This prevents the square tube from rotating and eliminates the need for a second screw, which, if required, would necessitate a larger tube.

Engineering Analysis:

The design was analyzed to guarantee that the welds and bolt would be sufficient to support the loads. This was done by finding the stress in the weld and comparing it to the shear yield strength of the welding material. The results indicate the structure should hold with a factor of safety of 2.52.

A 250 lb. load, the estimated maximum weight of the climber without his pack, was applied to the end of the structure while the main structure was rotated to 15° from vertical (**Error! Reference source not found.**).

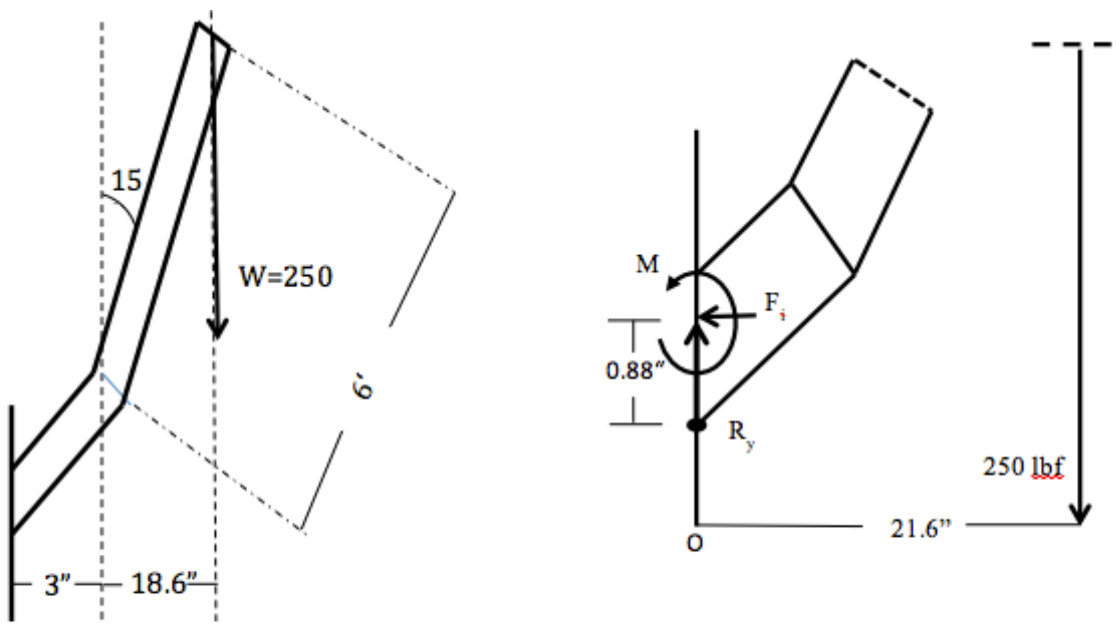


Figure 4 - Free Body Diagram of Wall Plate

The compressive force of the bolt was calculated using equation 1, where S_p is the proof strength and A_t is the tensile area of the bolt.

$$F_I = .9 \cdot S_p \cdot A_t \qquad \text{(Eq 1)}$$

$$F_I = .9 \cdot 30\ ksi \cdot .0775\ in^2$$

$$F_I = 2092.5\ lbf$$

Next the moment on the weld (Eq. 2) was then calculated using sum of moments.

$$M = 250\ lbf\ (21.6\ in.) - 2092.5\ lbf\ (0.88\ in.) \qquad \text{(Eq 2)}$$

$$M = 3558.6\ lbf \cdot in$$

Then the area moment of inertia of the weld was calculated to determine bending a stress. Since there are two vertical and two horizontal welds the total moment of inertia of the weld area is the sum of these individual welds. The area moment of inertias of the vertical welds (I_v) was found using equation 3, where L_v is the length of the vertical weld. The calculations assume that the throat (t) is equal to 0.1765".

$$I_v = \frac{{L_v}^3 \cdot t}{12} \qquad \text{(Eq 3)}$$

$$I_v = \frac{(1.767\ in)^3 \cdot .17675\ in}{12}$$

$$I_v = \frac{(1.767\ in)^3 \cdot .17675\ in}{12}$$

Similarly the area moment of inertia of a horizontal weld (I_H) was found using equation 4.

$$I_h = L_h \cdot t \cdot a^2 \qquad \text{(Eq 4)}$$

$$I_h = 1.25\ in \cdot (0.17675\ in)(0.88\ in)^2$$

$$I_h = 0.1771\ in^4$$

The area moment of inertia of the welded area is the sum of the vertical and horizontal welds (Eq 5).

$$I_X = 2 \cdot I_h + 2 \cdot I_V \qquad \text{(Eq 5)}$$

$$I_X = 2 \cdot (0.08126\ in^2) + 2 \cdot (0.1711 in^2)$$

$$I_X = 0.5047 in^2$$

Using the area of inertia of the welded area, the bending and transverse shear stresses were computed (Eq 6 & 7).

$$\sigma = \frac{M \cdot C}{I_X} \qquad \text{(Eq 6)}$$

$$\sigma = \frac{(3558.6\ lbf \cdot in) \cdot (0.88\ in)}{0.5047\ in^4}$$

$$\sigma = 6{,}204.8\ psi$$

$$\tau = \frac{W}{A} \qquad \text{(Eq 7)}$$

$$\sigma = \frac{250\ lbs}{2(1.767\ in + 1.25\ in)(0.17675\ in)}$$

$$\sigma = 234\ psi$$

The resultant stress was then calculated (Eq. 8) and compared with the shear strength yield of the Aluminum 4043 welding material (15,660 psi) to determine the factor of safety (Eq 9).

$$\sigma_R = \sqrt{\sigma^2 + \tau^2} \qquad \text{(Eq 8)}$$

$$\sigma_R = \sqrt{(6204.8\ psi)^2 + (234\ psi)^2}$$

$$\sigma_R = 6209.22\ psi$$

$$SF = \frac{S_{sy}}{\sigma_R} \quad \text{(Eq 9)}$$

$$SF = \frac{15{,}660\ psi}{6209.22\ psi}$$

$$SF = 2.52$$

Testing:

The wall plate was tested on a natural rock wall located in proximity to Auburn University (**Error! Reference source not found.**). The climbing device was inserted into the wall plate. A climber then climbed the device at various angles from the wall. The top weld failed when the device was pushed beyond its designed 15° angle to approximately 30° from vertical. However, within its designed operating range, the wall plates held and supported the structure and the climber. Additionally, it was observed that the expansion bolts that hold the plate to the wall need to be tightened enough that the anchors completely set in the drilled hole or the wall plate will become loose.

Figure 5 - Testing Wall Plate

Possible Improvements:

The primary concern with the current wall plate design is its weight. The team considered adapting the wall plate so that it may be made of lighter composite materials. However, after consultation with the polymer and fiber department, it was determined that the composite structure must be reinforced with aluminum. This would eliminate most of the weight savings. Additionally, the steel base of the hoist ring could be made of a lighter material such as aluminum.

3.3 Rotational Unit:

For detailed CAD drawings please see appendix.

Purpose:

The rotational unit (**Error! Reference source not found.**) connects the main structure to the wall plate and allows the structure to rotate relative to the wall plate. This allows the device to operate on surfaces that are not perfectly smooth or vertical.

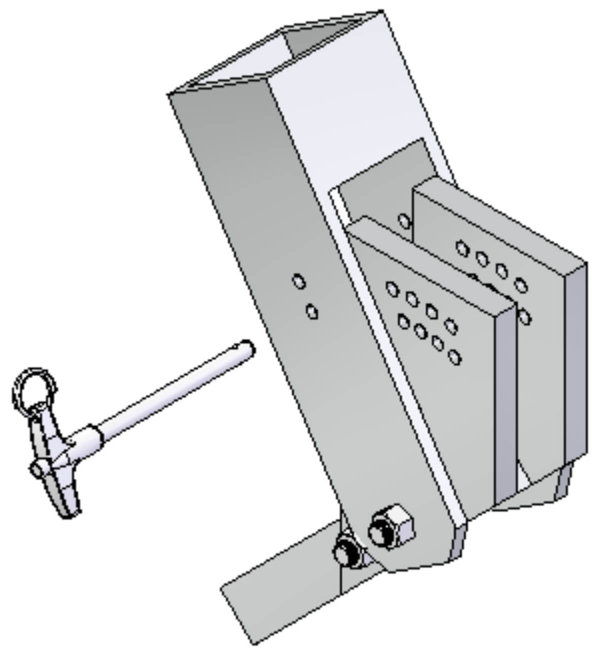


Figure 6 - Rotational Unit

Design Requirements:

- Securely connect the main structure and the wall plate.
- Allow the main structure to rotate into and out from the climbing surface.
- Minimize Weight.
- Minimize Volume.

Design Description:

The rotational unit consists of an aluminum bar, two detent plates, a coupling, a reinforcement rod, two bolts, nuts and a pushpin (Figure 8 & 9). The bar is inserted into a corresponding tube in the wall plate to connect the device to the wall plate. The two detent plates are bolted to the bar and have two bolt hole arcs. These two arcs each have four holes separated by 6°. Since the arcs are staggered, this creates stops at 3° increments. The corresponding holes in the coupling allow the rotation of the device to be locked. This is done by pivoting the coupling about a bolt and passing a pushpin through the holes in both the coupling and plates.

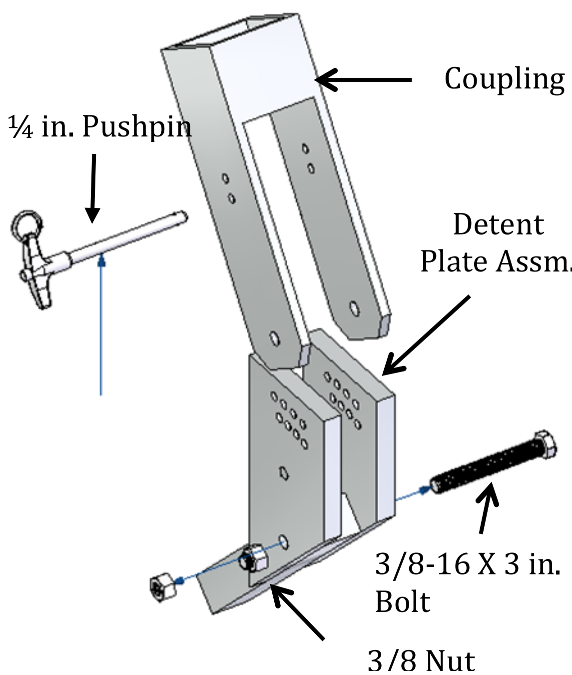


Figure 8 - Exploded View of Rotational Unit

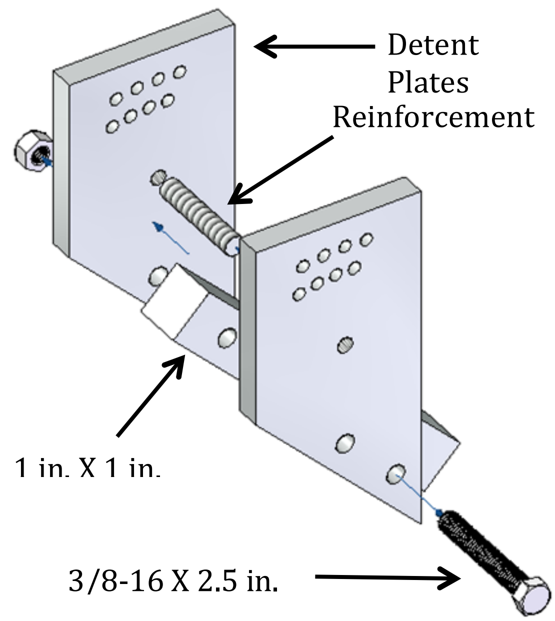


Figure 9 - Detent Plate Assembly

Changes:

The rotational unit presented at the critical design review incorporated a ratchet system (**Error! Reference source not found.**). A prototype of this system was built and tested at the Auburn University Repel tower. During this test, it was determined that the ratchet teeth were spaced to far apart. As a result, the top of the ladder could sway considerably before the pawl engaged with a tooth. Due to the high loads, smaller teeth were not a viable option and the ratchet design was rejected in favor of the current system.

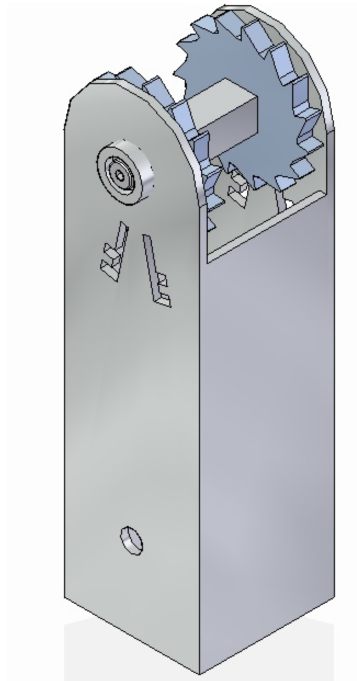


Figure 10 - Previous Rotational Unit Design

Testing:

The rotational unit was tested by taking the device out to a natural rock face (**Error! Reference source not found.**). A wall plate was attached to the surface and the rotational unit and main structure were connected. A climber then rotated the unit to the various available stops and proceeded to climb. The testing revealed a small amount of play in the unit and a considerable amount of force needed to place the pin.

Figure 11 - Testing Rotational Unit

Engineering Analysis:

Analytical calculations were performed to determine if the rotational unit could support the expected loads. The analysis was performed for the worst case scenario of the device being rotated 15° from the wall and the climber's 300 lb. center of mass being located at the top of the device. The length was extended to 7 ft. to compensate for any connection joints, ect. The calculations show that the rotational unit should be capable of supporting the loads with a factor of safety of 2.7 due to tear out from one hole in the bolt hole arc to another.

First, the forces at the pivot bolt (P) and the locking pushpin (L) at the 15° stop located on the inner 3.5" diameter arc were determined by using sum of forces and moments (**Error! Reference source not found.**).

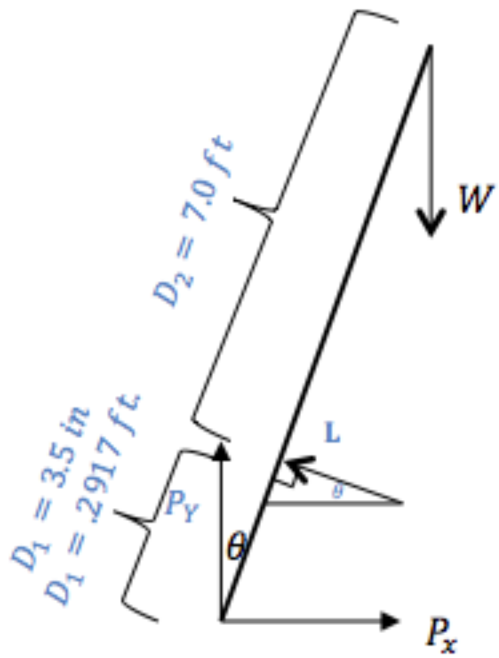


Figure 12 - Free Body Diagram of Rotational Unit

$$\sum M_p = 0$$

$$0 = L(L_1) - W(\sin\theta)(D_1 + D_2)$$

$$0 = L(.2917\ ft) - 300lbf(\sin 15°)(7.2917\ ft)$$

$$L = 1941\ lbf$$

$$\sum F_x = 0$$

$$P_x - L \cdot \cos\theta = 0$$

$$P_x = L \cdot \cos\theta$$

$$P_x = L \cdot \cos 15°$$

$$P_x = 1941 \text{ lbf} \cdot \cos 15°$$

$$P_x = 1875\ lbf$$

$$\sum F_y = 0$$

$$P_y + L \cdot \sin\theta - W = 0$$

$$P_y = -L \cdot \sin\theta + W = 0$$

$$P_y = -1941\ lbf \cdot \sin 15° + 300\ lbf$$

$$P_y = -202\ lbf$$

$$P = \sqrt{P_x + P_y}$$

$$P = \sqrt{(1875\ lbf)^2 + (-202\ lbf)^2}$$

$$P = 1886\ lbf$$

Bolt Shear:

Shear stress (τ_s) in the bolts was calculated (Eq 10) to confirm that the bolts would not shear under load. In these calculations the cross sectional area of the bolts (A_S) (Eq 11) is doubled because the bolts are in double shear. The calculated stress was then compared to the shear strength yield of aluminum 6061-T6 (22,800 psi) to determine the factors of safety (Eq 12).

$$\tau = \frac{F}{A} \qquad \text{(Eq 10)}$$

$$A = \pi \cdot r^2 \qquad \text{(Eq 11)}$$

$$SF = \frac{S_{sy}}{\tau_S} \qquad \text{(Eq 12)}$$

Pivot:

$$A = \pi \cdot r^2 \qquad \tau = \frac{F}{A} \qquad SF = \frac{S_{sy}}{\tau}$$

$$A_S = \pi\left({}^{3}\!/_{8}\ in.\right)^2 \qquad \tau_S = \frac{1886\ lbf}{.8836\ in^2} \qquad SF = \frac{22{,}800\ psi}{2{,}134\ psi}$$

$$A_S = .4418\ in^2 \qquad \tau_S = 2{,}134\ psi \qquad SF = 10.68$$

Lock:

$$A = \pi \cdot r^2 \qquad \tau_L = \frac{F}{A} \qquad SF = \frac{S_{sy}}{\tau_L}$$

$$A_L = \pi\left({}^{1}\!/_{4}\ in.\right)^2 \qquad \tau_L = \frac{1941\ lbf}{.3926\ in^2} \qquad SF = \frac{22{,}800\ psi}{4{,}944\ psi}$$

$$A_L = .1963\ in^2 \qquad \tau_L = 4{,}944\ psi \qquad SF = 4.61$$

Bearing Stress:

The effective area used for bearing stress (A_B) is the projected area perpendicular to the applied force (Eq. 13).

$$A_B = t \cdot d \qquad \text{(Eq 13)}$$

This area is doubled in the stress calculations because it passes through two plates or walls. Using this area, the bearing stress was calculated to verify that the compressive force of the bolts against the hole wall was within allowable limits. This was compared to the bearing yield strength of the material (56,000 psi) to calculate the factors of safety.

Pivot-Coupling:

$A_B = t \cdot d$

$A_B = .250\ in \cdot .375\ in$

$A_B = .0938\ in^2$

$\sigma = \frac{F}{A}$

$\sigma_B = \frac{1886\ lbf}{.1875\ in^2}$

$\sigma_B = 10{,}059\ psi$

$SF = \frac{S_{By}}{\tau_B}$

$SF = \frac{56{,}000\ psi}{10{,}059\ psi}$

$SF = 5.56$

Pivot- Detent Plate:

$A = t \cdot d$

$A_B = .500\ in \cdot .375\ in$

$A_B = .1875\ in^2$

$\sigma_B = \frac{F}{A}$

$\sigma_B = \frac{1886\ lbf}{.3750\ in^2}$

$\sigma_B = 5{,}029\ psi$

$SF = \frac{S_{By}}{\tau_B}$

$SF = \frac{56{,}000\ psi}{5{,}029\ psi}$

$SF = 11.13$

Lock-Coupling:

$A_B = t \cdot d$

$A_B = .250\ in \cdot .250\ in$

$A_B = .0625\ in^2$

$\sigma = \frac{F}{A}$

$\sigma_B = \frac{1{,}941\ lbf}{.125\ in^2}$

$\sigma_B = 15{,}528\ psi$

$SF = \frac{S_{By}}{\tau_B}$

$SF = \frac{56{,}000\ psi}{15{,}528\ psi}$

$SF = 3.61$

Lock- Detent Plate:

$A_B = t \cdot d$

$A_B = .500\ in \cdot .250\ in$

$A_B = .125\ in^2$

$\sigma = \frac{F}{A}$

$\sigma_B = \frac{1{,}941\ lbf}{.250\ in^2}$

$\sigma_B = 7{,}764\ psi$

$SF = \frac{S_{By}}{\tau_B}$

$SF = \frac{56{,}000\ psi}{7{,}764\ psi}$

$SF = 7.21$

Tearout:

The effective area used for tearout stress (A_T) is given by Eq 14, where e is the distance to the nearest edge or hole, d is the diameter of the hole and t is the thickness of the material.

$$A_T = 2\left(e - \frac{d}{2}\right) \cdot t \qquad \text{(Eq 14)}$$

This area is doubled in the stress calculations because it passes through two plates or walls. Using this area, the tearout stress was calculated to ensure that the bolts would not tear out of the material to the nearest hole or edge. This was compared to the shear yield strength of the material to calculate the factors of safety.

Pivot-Coupling:

$$A_T = 2\left(e - \frac{d}{2}\right) \cdot t$$

$$A_T = 2\left(.750\ in - \frac{.375\ in}{2}\right) \cdot .250\ in$$

$$A_T = .2813\ in^2$$

$$A_B = .0938\ in^2$$

$$\tau = \frac{F}{A}$$

$$\tau_T = \frac{1{,}886\ lbf}{.5626\ \ in^2}$$

$$\tau_T = 3{,}352\ psi$$

$$SF = \frac{S_{sy}}{\tau_T}$$

$$SF = \frac{22{,}800\ psi}{3{,}352\ psi}$$

$$SF = 6.80$$

Pivot – Detent Plate:

$$A_T = 2\left(e - \frac{d}{2}\right) \cdot t$$

$$A_T = 2\left(.500\ in - \frac{.375\ in}{2}\right) \cdot .500\ in$$

$$A_T = .3125\ in^2$$

$$A_B = .0938\ in^2$$

$$\tau = \frac{F}{A}$$

$$\tau_T = \frac{1{,}886\ lbf}{.6250\ \ in^2}$$

$$\tau_T = 3{,}017\ psi$$

$$SF = \frac{S_{sy}}{\tau_T}$$

$$SF = \frac{22{,}800\ psi}{3{,}017\ psi}$$

$$SF = 7.56$$

Lock-Coupling:

$A_T = 2\left(e - \frac{d}{2}\right) \cdot t$

$A_T = 2\left(.500\ in - \frac{.250\ in}{2}\right) \cdot .250\ in$

$A_T = .1875\ in^2$

$A_B = .0938\ in^2$

$\tau = \frac{F}{A}$

$\tau_T = \frac{1{,}941\ lbf}{.3750\ \ in^2}$

$\tau_T = 5{,}176\ psi$

$SF = \frac{S_{sy}}{\tau_T}$

$SF = \frac{22{,}800\ psi}{5{,}176\ psi}$

$SF = 4.40$

Lock – Detent Plate:

$A_T = 2\left(e - \frac{d}{2}\right) \cdot t$

$A_T = 2\left(.242\ in - \frac{.250\ in}{2}\right) \cdot .500\ in$

$A_T = .1170\ in^2$

$A_B = .0938\ in^2$

$\tau = \frac{F}{A}$

$\tau_T = \frac{1{,}941\ lbf}{.2340\ \ in^2}$

$\tau_T = 8{,}295\ psi$

$SF = \frac{S_{sy}}{\tau_T}$

$SF = \frac{22{,}800\ psi}{8{,}295\ psi}$

$SF = 2.75$

3.4 Main Structure Subassembly:

For detailed CAD drawings please see appendix.

Purpose:

The purpose of the main structure is to provide the climber with an easy way of climbing 9 ft. at a time and to provide support while the next wall plate is installed.

Design Requirements:

- Firmly support the climber as he installs the next wall plate.
- Provide an easy way to climb 9 ft.
- Allow minimum bending when subjected to a load.
- Minimize weight.

- Minimize volume.

Design Changes:

The original prototype used aluminum extrusion to make the main structure. This material selection clearly needed to be improved because the weight of the device was too much. While significant weight reductions were achieved by changing the design of the ratchet and using only one rotational unit, much of the total weight remained in the main structure itself. Research into weight saving structural material resulted in several different options for the next prototype. The off the shelf option was to purchase carbon fiber tubing and replace the aluminum extrusion with this much lighter material. Based on a comparison of costs and availability of appropriate diameter tubing, we purchased several sections of carbon fiber tubing from Forte Carbon. The diameter of this carbon fiber tubing is 2”. A redesign of the joints between the tube sections and the connection to the rotational unit was necessary based on the new geometry. An additional option was made available by the research of the doctoral student assigned to advise our senior design team. His post-graduate research was in the Polymer and Fiber department and focused on manufacturing high strength hybrid composite structures from reinforced carbon fiber yarns. We were able to assist in the development and manufacturing of these structures over the course of this past semester. The end result is a hybrid carbon fiber tube that is several pounds lighter than the commercially available tubing. None of these hybrid structures have ever been made before, and a patent is currently pending on the design. Since the technology is so innovative,

much of the groundbreaking research to improve the basic concept has been done by this team. The manufacturing process in particular has many possible methods to improve the structure. In fact, several elements can be significantly tweaked to tailor the strength of each structure to the expected application. For our design, bending strength and compressive stress were the most critical areas, and our manufacture and testing of the composite structures focused on them. Other applications may experience more tensile stress, shear or torsion, and the design/manufacture can be modified to address these failure modes. The adaptable nature of the manufacturing process allowed our team to maximize our engineering design skills to minimize overall weight while maximizing the performance of the main support structure.

Forte Carbon:

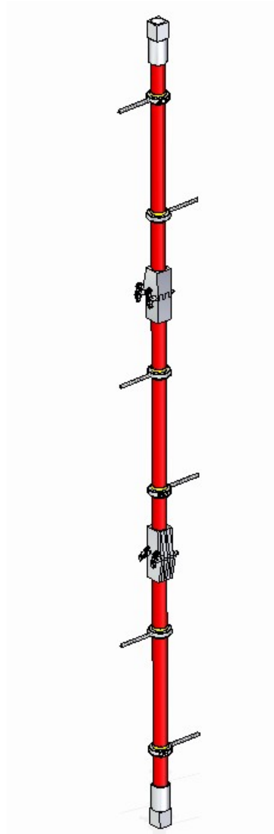


Figure 13 - Forte Carbon Main Structure

The main structure for both the Forte Carbon and hybrid composite follows the above design. The nature of this design is modular to allow multiple design changes of individual components without necessitating cascading design changes. The only difference is the material that makes up the support structure (shown as red in FIG). Some small sizing differences exist, but the basic concept remains the same. Originally, the 3 section approach was used when making the Forte Carbon prototype, but that has since been reduced to only 2 sections. The reasons for this will be detailed in the Testing section below. The end piece of the main structure consists of a cylindrical portion and square portion. The cylindrical part encompasses the composite beam and the square part attaches to the

rotational unit. A pin will then secure the connection between the main structure and the rotational unit. This connection will be gravity fed as well. Only one end piece is needed per unit. The modular nature of this end piece design makes it possible to test many different versions of the composite main structure on the same rotational unit with minimal effort.

In order to climb the composite structure, foot pegs must be installed. Drilling into such structures is ill advised or impossible, so an alternative design was necessary. The method that we came up with is to install metal collars that tighten down with bolts. Each collar could then have a high strength bolt threaded into the side (but not through the composite structure). These bolts stick out at right angles to the device and provide a convenient foot peg for climbers. As can be seen in Figure 13, the original design only placed one foot peg per collar, but that has since been changed. Physically testing the device showed us that putting 2 foot pegs opposite each other on each collar was far more ergonomically feasible. The placement of each collar was also refined during this process to make it as easy as possible for the climber to safely reach the top of the device. A rubber sleeve is wrapped around the composite beam underneath the collar. This helps disperse the compressive forces from the collar and prevents the collar from cutting into the composite. Testing has shown that this method of securing foot pegs works well.

A collar attached to the top of the device has an eyebolt threaded into it that allows the climber to attach himself to the top of the device with a quick draw. This affords hands free capability once the climber is clipped in. An alternative is

to loop a quick draw around the device itself and connect this loop to the waist harness. Both options leave the airman with the ability to safely use both hands to drill and install the next anchor plate.

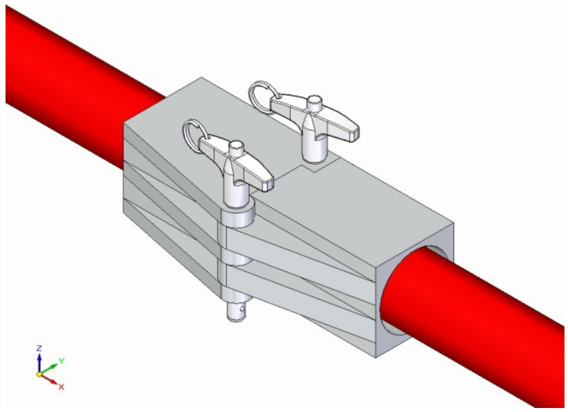


Figure 14 - Hinge for Composite Prototype

The hinges are made of aluminum and allow the device to be stored in a collapsed position. The use of high shear strength pins gives the ease-of-use factor while keeping the overall integrity of the device high. The composite structure cannot have holes drilled in the sides or this would compromise the structure. In order to address this issue, the hinges have cylindrical holes bored out on either side that allow the composite beam to slide inside the aluminum hinge (Figure 14). A two part resin epoxy is then poured into the gap around the beam and hinge. The large amount of surface area in contact with the epoxy results in a very strong bond between the aluminum and composite. This process will be referred to as potting in the following sections. Care must be taken to pot the composite beam at a perfect 90° angle to the hinge surface or this will cause the structure to lean to one side when deployed.

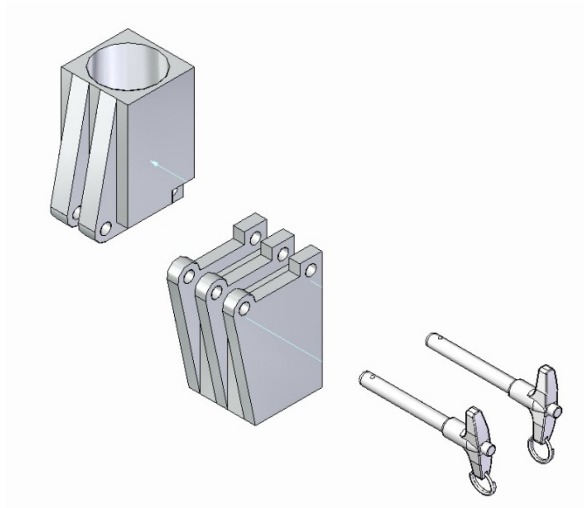


Figure 15 - Exploded View of Composite Hinges

The hinge design allows different sections of composite structure to be switched in if one section becomes damaged for whatever reason. Testing showed very small amounts of play in these joints. Much of this play was eliminated by replacing the pin on the left (Figure 15) with a nut and bolt. This allows the hinge to still rotate freely, while cutting down on the side-to-side play. Only the pin on the right of the figure ever needs to be removed when storing/deploying the device. Since these hinges are almost entirely hollow, the total weight added is comparatively small. Additional design refinement has eliminated even more extraneous aluminum material from each hinge. The corners can have small holes drilled in them to shave a few ounces off without becoming a failure point.

Hybrid Composite Structure:

A significant amount of effort was placed into the manufacture and development of the hybrid composite structure option. Since there was no precedent to follow, this effort required both design work and developing the

manufacturing procedure. The primary component of these high strength structures is the carbon fiber yarns that make up the main load-bearing skeleton (Figure 16). Carbon fiber has an extremely strong tensile strength because of its atomic structure. Fairly recent advances have only now made it economical to use this material in the commercial workplace because of its original high cost. The fibers may be formed or woven into any number of configurations and painted with resin to produce lightweight but strong structural components. The carbon fiber materials that we used were large spools of straight carbon fiber. We used 12 spools of carbon fiber, with each spool unwinding 3 thousand individual carbon fibers. By mounting these spools on freely rotating pivots, we were able to produce carbon fiber yarns with 36 thousand individual carbon fiber strands forming the core. The carbon fiber we used is also pre-impregnated with resin. This resin is rated for room temperature and cures only at a high temperature. This allowed us to make support structures with the yarns and then cure them. The result is a high strength, low weight structure that now has high rigidity. One of the main downsides of using carbon fiber structural elements is their tendency to fray and break since they cannot withstand large shear forces. In order to combat this issue, a protective sleeve must be placed over the strand of fibers. A braiding machine is used to weave this protective sleeve.

Figure 16 – Sample of Open Structure

The braiding machine is used in conjunction with a motorized capstan that pulls the yarn onto a spool (Figure 17). Once the composite carbon fiber yarn has been manufactured, it is then placed on the braiding machine. The yarns are then braided over a metal, waxed pipe called a mandrel (Figure 18). The same basic braid that formed the individual yarns is now duplicated on a larger scale over the mandrel. The yarns are secured to each end of the mandrel and are then baked in an oven for several hours, curing the pre-preg carbon fiber. The mandrel is then removed, and the end product is an open composite structure.

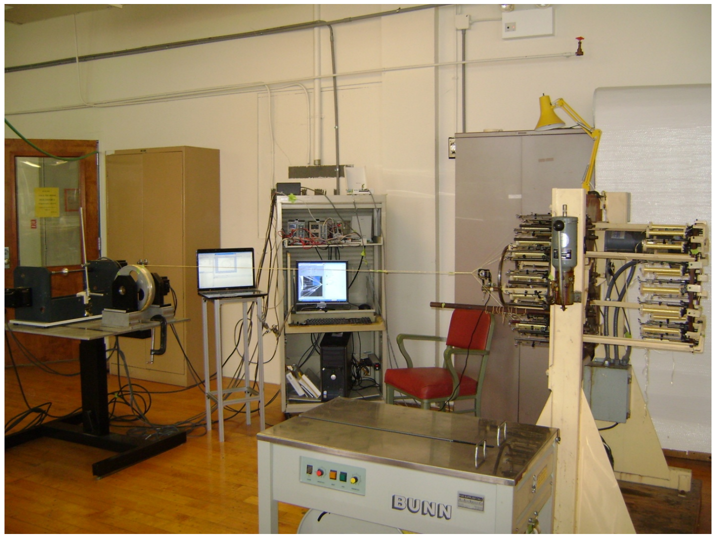


Figure 17 - Computer Controlled Take-up System

The protective sleeve is made out of a high tensile strength material called Vectran. It is similar to fishing line, only with a very high-test pound rating. The braiding structure of this sleeve is extremely important to the success of the yarn. We used a new braiding structure called True Triaxial Braiding, which has been patented by two Auburn University engineering professors (including Dr. Beale, our advisor for this project). In order to fully explain the manufacturing and design process, it is necessary to distinguish between axial yarns and braiding yarns. Axial yarns are yarns that are pulled straight through the braiding machine, capable of supporting high tensile loads since they are almost perfectly straight. The braiding yarns are the yarns that travel around the core and are what connects everything together. A long strand of yarn is wound on a bobbin and mounted on a carrier. Each carrier on the braiding machine has a twin carrier that travels in the opposite direction. As each carrier travels around in a circular path, it oscillates to produce the braid. One carrier will always cross over the top, while the other carrier will always cross over the bottom when they meet. The physical

placement of the yarns on specific carrier pairs produces very different braid patterns. The specific configuration that we used will not be divulged here, in sensitivity to a pending patent. In addition to the basic braid structure that is chosen, the number of axial and braiding yarns can be varied. For instance, we chose to use 8 braiding yarns and 4 axial yarns of Vectran to weave the protective sheath around the core of carbon fiber. The same basic structure is then repeated on a larger scale when we weave the newly manufactured carbon fiber yarns into a beam. In that case, we used 8 braiding yarns and 8 axial yarns of the Composite Carbon Fiber Yarn. An extensive design process was used to determine this specific braider configuration. We created a computer model of many braid structures and tested them using Finite Element Analysis. A subsequent section details this process and its results.

Figure 18 - Mandrel

An additional factor in manufacturing both the yarn and composite structures is the pitch rate. Basically, it is how far each braiding yarn advances axially as it completes each full rotation around the braiding machine. The pitch

rate is what determines how ‘open’ the yarn or composite structure is made. It is important to leave enough spacing on the composite yarns so that the carbon fiber core is exposed, while protecting the core. The exposed carbon fiber then bonds with the other yarns when it is braided into a structural component. The pitch of the structural components is far greater than when you make the yarns. This is for multiple reasons: you use far less total material (saving both weight and significant manufacturing time), and you can achieve engineering requirements with very little material because it is so strong. The primary manufacturing tool to maintain pitch rate is the motorized capstan. This sets a constant pitch rate for the composite yarns while simultaneously winding them up onto a spool. The method for this is also a patented design by the graduate student who we worked alongside during this project. The larger pitch rate used when manufacturing the open structures with the mandrel is better done by hand actually. This allows for the correction of errors that quickly escalate on the large scale, but are negligible when making the yarn.

Figure 19 - Open Structure With Inner Sleeve Prior to Resin

Figure 20 - Placement of Inner and Outer Sleeves

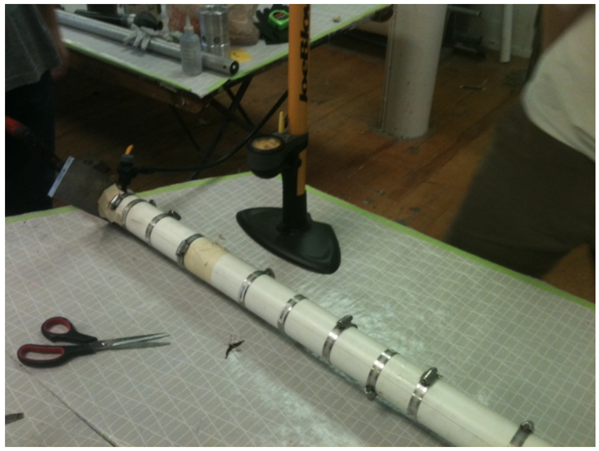


Figure 21 - Clamshell Support With Pressurized Bicycle Tube

Figure 22 - Clamshell Support With Outer Sleeve Pressurization by Vacuum Bagging

Once the open structures have been woven, cured and taken off of the mandrels, additional work is required to improve the strength. As was explained above, each braid point has a small amount of resin connecting each yarn. However, if these bonds are broken, the overall strength decreased greatly.

Multiple options exist to address this problem. The first composite

structure prototype that we manufactured used a carbon fiber sleeve. A sleeve is inserted through the inside of the tube and painted with resin (Figure 19). This basically makes the entire surface area of the structure connected and the beam is no longer 'open'. In order to improve the compressive hoop stress expected from the foot pegs, this inner layer of carbon fiber was cured with a pressurized bicycle tube pushing out on it (Figure 21). Once curing was completed, the tube was removed. An additional layer of carbon fiber sleeve was placed on the outside and painted with resin (Figure 20). This layer is then placed inside a PVC pipe that formed a type of clamshell support, and then vacuum bagged. This created pressure pushing into the beam and improved bonding. The inner and outer sleeves were cured at the same time, with two opposite pressures combining to maximize compressive hoop strength and total bonded surface area (Figure 22). The end result is extremely strong, while weighing only about a quarter pound per foot.

Many other options remain to improve the strength of the beams while reducing weight. For instance, a much lighter sleeve on the inside and outside will produce similar strength results but weigh quite a bit less. This is because the sleeve is not a load-bearing element, it mostly just secures strong bonds for the composite carbon fiber yarns that form the inner skeleton of the beams. Also, in lieu of using sleeves at all, knots can be tied at each braid point with high tensile strength Kevlar, and then painted with resin. Further testing is necessary at this point to test this new prototype out. The final structure will remain a true open structure and will weigh considerably less than the existing composite prototype.

The only limiting factor for our team right now is time and budget. Further funding for Auburn University could easily result in additional improvements to these highly promising composite support beams and open new avenues for their use by the Air Force.

Testing:

Currently, two lightweight prototypes have been made—the Forte Carbon prototype and our first composite prototype. The Forte prototype has served as an excellent proof of concept for our redesign of the total device and is our primary tool to refine the design. Testing this prototype gave us valuable information on ergonomic considerations such as foot peg location. We also discovered that only 2 sections are required to hit our target distance from anchor to anchor. The full 3 section prototype proved to be far too flexible at the top, and exceeded the necessary distance. The modular nature of the device allowed us to simply remove one support beam section. The 2 section version improved the total amount of flex, reduced the moment arm on the wall plate, and still met our target requirements. The average distance from anchor point to anchor point is around 8.5 ft.

Bending tests were performed on the composite structures manufactured in-house as well as on the Forte carbon fiber material to insure that they would be safe to use in prototypes as well as to determine their moduli of elasticity.

To perform the bending tests, specimens were made by potting the ends of sections of each material in resin, in large steel pipe fittings in order to allow a press and v-blocks to be used to hold the sections in place and create a

cantilevered beam. A dial indicator was used to measure the deflection at the end of the section while weight was incrementally added to straps attached to the end of the section. After the maximum load was applied, all of the weight was removed and a deflection measurement was taken. This process was completed twice for each material specimen, except for the newest open structure. It was taken to failure on the first run.

As can be seen in figure 23, the point where the load is applied is not the same point where the deflection measurements were taken. To normalize the deflection to the point where the load was applied, the ratio of the distance from the fixed end to the point of load application and the distance from the fixed end to the point of deflection measurements were used as shown below:

$$v_{point\ of\ loading} = v_{point\ of\ measurement} \times \frac{L_{point\ of\ loading}}{L_{point\ of\ measurement}}$$

Using the deflection at the point of loading and the moment of inertia—calculated using $I = \pi(d_o^4 - d_i^4)/64$ for the Forte and sleeved specimens and by analysis software for the open structure—the moduli of elasticity could then be calculated using the equation:

$$E = \frac{PL_{pl}^3}{3v_{pl}I}$$

The average modulus of elasticity for each test run as well as the plots of the experimental data can be seen below.

Figure 23 - Bending Test Set -Up

Table 1 - Moduli of Elasticity Results:

Material	Run	E (ksi)
Forte Carbon Fiber	1	1,480.33
	2	2,246.519
Sleeved Structure	1	664.586
	2	732.951
Open Structure	1	151.062

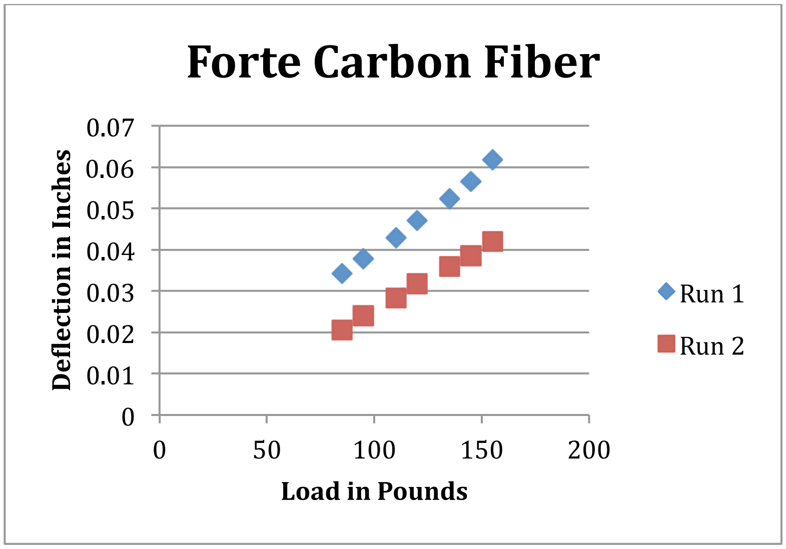


Figure 24 - Load vs. Deflection for Forte Carbon Fiber

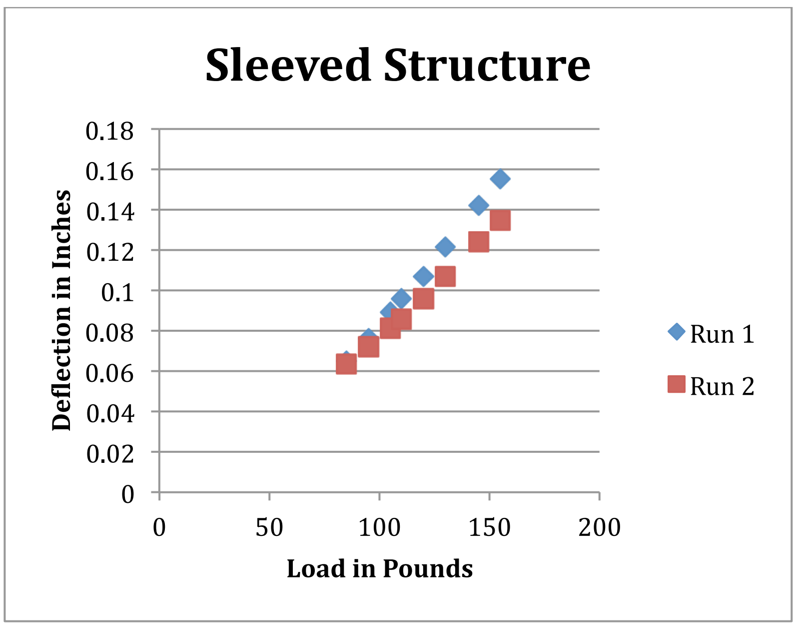


Figure 25 - Load vs. Deflection for Sleeved Structure

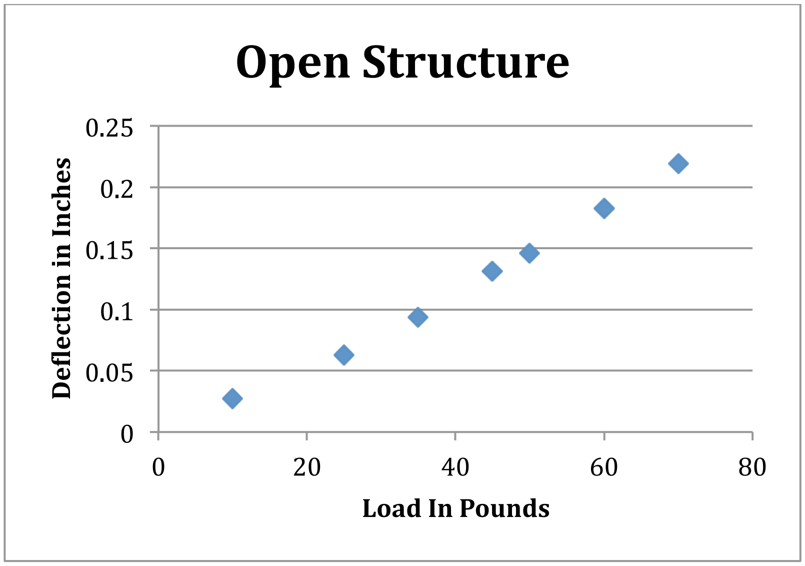


Figure 26 - Load vs. Deflection for Open Structure

The average moduli of elasticity calculated are larger in the second run compared to the first run for each specimen. This is believed to happen because of hardening and toughening of the resin used to pot the sections as a result of loading. When the specimens were unloaded after the first run there was still some deflection measured, probably due to compression in the resin. Compressed resin is harder than uncompressed resin and therefore can account for the difference in moduli of elasticity.

Lab testing is not the only testing done with these materials. To date a fully functional prototype made using Forte carbon fiber has been test climbed in a natural environment and has had no problems. Other prototypes are in the process of being made using the other two materials and will be tested the same way before the competition.

3.5 Fast Ascender Subassembly:

Purpose:

The fast ascender is responsible for getting the remaining Airmen to the top safely and quickly once the first Airman has completed the ascent and secured a fixed line.

Design Requirements:

- Reduce the output required for the climbers to reach the top.
- Ascend as close to the target speed of 45 ft./min. as possible.
- Minimize weight.
- Minimize volume.

Design Changes:

Initially, we designed a fast ascender device that was powered by the same drill used to drill holes in obstacle face. This design was a capstan winch that utilized a worm gear to multiply the torque of the drill as well as hold the climber stationary when the device was not powered (Figure 27). The drafts of this fast ascender device were completed and a final cost to machine the product was determined. Unfortunately, the cost and time required to manufacture the fast ascender we designed was going to be too high. That, combined with the risk that when all the parts were assembled the product would not work as intended, led us to go back to the drawing board for this subassembly.

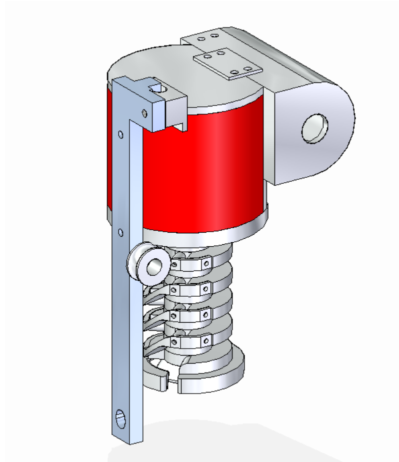


Figure 27 - Original Fast Ascender Design

The next solution was to simulate the Atlas APA – 5 Lightweight Powered Ascender (Figure 28) using the SP-CW Winch (Figure 29) powered by a Honda 4 stroke motor. The reason for simulating the Atlas device and not just ordering one to use is because the device is only available to the Department of Defense. This winch and motor system gives an accurate portrayal of what the Atlas device can do, however, it is slightly heavier, louder and requires gasoline.

Once we were aware that Atlas devices would be available for use at the competition, we decided to use them for our solution. We decided that, while the Atlas device is expensive for the military, it performs very well, and finding a good solution for getting the first person up the obstacle was the more important problem to solve and a better use of time and resources.

Figure 28 - Atlas APA - 5

Figure 29 - SP - CW Winch

3.6 Carrying and Organizing Gear Subassembly

Purpose:

The gear subassembly is responsible for allowing the lead Airman to easily carry all the necessary tools while ascending the main structure.

Design Requirements:

- Allow Airman easy access to necessary tools
- Safely access tools without dropping
- Provide hands free option
- Minimize time
- Minimize volume

Design Changes:

Most of the gear was carried in small bags, which made it difficult to locate specific items. In addition, the drill was carried using a long strap, which was difficult to access when necessary.

After analyzing the difficulties in climbing due to the gear, considerations for forming alternative ways for carrying the gear were developed. The wall plates will be attached to the harness using carabiner-like hooks that allow for secure portable access. The bolts and wrench will be carried in a quick open and close pouch in order to minimize dropping. The drill will be attached using a spring like cord, which will give the user the ability to easily reach for the device when necessary without much difficulty.

4.0 Technical Resource Tracking:

4.1 Total Weight

The following tables list the updated total weight of each subassembly in the design. Since the fast ascender subassembly is just one part it is not listed in a table. The Atlas device weighs 15 lbs. It is worth noting that the team is constantly working to lower the overall weight of the device and as testing continues we expect the weight decrease.

Table 2 - Total Weight of Wall Plate Subassembly:

Item #	Part	Item	Part Quantity	Individual Weight (lbs)	Total Weight (lbs)
1	Wall Plate	Plate	10	0.617665	6.176650
2	Wall Plate	Hoist	10	0.197123	1.971230
3	Wall Plate	Plug	10	0.296213	2.962130
4	Wall Plate	Anchor Bolts	20	0.112436	2.248720
				TOTAL:	13.358730

Table 3 - Total Weight of Rotational Subassembly

Item #	Part	Item	Part Quantity	Individual Weight (lbs)	Total Weight (lbs)
1	Ratchet	Coupling	1	0.648649	0.648649
2	Ratchet	Ratchet Gear	2	0.205885	0.411770
3	Ratchet	Pawl	2	0.078859	0.157718
4	Ratchet	Half Pin	2	0.103909	0.207818
5	Ratchet	Lock Pin	2	0.002899	0.005798
6	Ratchet	Ratchet Mount	1	2.141849	2.141849
7	Ratchet Coupling	2" x 2" Stock	2	0.661049	1.322098
8	Ratchet Coupling	Bracket	2	1.310669	2.621338
9	Ratchet Coupling	Flanged Head Bolt & Nut	8	0.064429	0.515432
10	Ratchet Coupling	Top Bar Spacer	4	0.855746	3.422984
11	Ratchet Coupling	Side Bar Spacer	4	0.213937	0.855748
				TOTAL:	12.311202

Table 4 - Total Weight of Main Body Subassembly

Item #	Part	Item	Part Quantity	Individual Weight (lbs)	Total Weight (lbs)
1	Main Body	Forte Carbon Tube	3	1.200000	3.600000
2	Main Body	Hinge	2	0.162621	0.325242
				TOTAL:	3.925242

4.2 Battery Budgeting

There are two batteries that will be used in our design. The first is the battery that is included with the Atlas device. It is capable of charging in less than 30 min. and can ascend a minimum of 600 ft. on a single charge. This distance is greater than the distance we expect the Airmen to have to cover during operation.

The other battery is included with the Dewalt drill that will be used to drill anchor holes in the climbing surface. The battery is a 36v battery that charges in 1 hr. Testing has shown that the battery can provide power to drill over 25 holes in varied material consistently before losing power. The obstacle we are

designing for will only require 20 holes to be drilled so this battery will also work for our design.

5.0 Budget:

The expected bills of materials for the current design are broken down by subassembly and are shown in the following tables. The Atlas device is not listed since a price for that specific model could not be acquired. The price of the winch and motor that is simulating the Atlas device is $939.00. For a complete list of purchases and suppliers please refer to the appendix.

Table 5 - Total Cost of Main Structure Subassembly

Item #	Part	Item	Part Quantity	Part #	Total Cost
1	Carbon Fiber Tubing		2	-	$192.00
2	Steps Threaded*	STL Threaded Rod 3'	6	90322A100	$7.17
3	Shaft Collar 2" ID	2 Piece Shaft Collar	5	6157K25	$88.20
4	Rubber Shaft*	Neoprene Rubber	6	1MVZ4	$3.20
5	3tab hinge*	AL Stock 2.5" X 3" X 3'	1	8975K272	$19.87
6	2tab hinge*	AL Stock 2.5" X 3" X 3'	1	8975K272	$19.87
7	End Sleeve*	AL Stock 2.5" x 2.5" x 1'	1	9008K571	$23.75
8	Resin	Hardener Epoxy	1	635314	$68.00
9	Hex Bolt	3/8" Dia.	1	AWF	$0.40
10	Eye Bolt	3/8-16" threaded end	1	3013T471	$3.59
11	Hex Nut	3/8"	1	655449	$0.12
12	T Handle Lock Pin	3/8" dia. 2.5"	1	90293A314	$25.91
				Total:	$452.08

Table 6 - Total Cost of Rotational Unit Subassembly

Item #	Part	Item	Part Quantity	Part #	Total Cost
1	Main Coupling*	2-1/2" X 2-1/2" Sq. Tube	1	6546K313	$16.54
2	Angle Plate*	AL Plate 1/2 in thick	2	8975K223	$14.28
3	T Handle Lock Pin*	3/8" dia. 3"	2	5RER9	$71.80
4	Hex Bolt	3/8"	2		$0.80

5	Hex Nut	3/8"	2		$0.24
6	Threaded Rod	3/8-16" threaded rod	1	94435A344	$1.49
7	AL Insert Block*	AL 1.5" X 2" X 1'	1	8975K311	$14.00
				Total	$119.15

Table 7 - Total Cost of Wall Plate Subassembly

Item #	Part	Item	Part Quantity	Part #	Total Cost
1	Wall Plate Backing	8" X 1/2" X 3'	10	8975K223	$71.20
2	Insert Tubing	1.25" X 1.25" X 3' 1/8" t	10	88875K583	$17.48
3	Paint and Primer	Black Paint and Primer	4	-	$14.68
4	Bracket Screws	3/8-16, 1-1/4" long (Pack-25)	1	90275A626	$5.31
5	Fixed Wedge Bolts	3/8" X 2-3/4"	20	#41	$99.00
6	Rotary Hammer Drill	36 Volt Cordless	1	DC223KL	$734.36
7	Slimline Elite Rope	10.3 mm Dia, 200 feet	1	165510	n/a
8	Carabiners	Large D Auto Lock	8	144016	n/a
9	Alpine Body Harness	-	1	34588	n/a
10	Helmet	-	1	51306	n/a
11	Quickdraws	-	6	110187	n/a
12	4 step aider	1"	1	AIDE002	$34.95
13	Alpine Equalizer	3'	1	630032	$35.95

6.0 Requirements:

6.1 System Requirements:

- Objective Requirements for System:
  - Velocity (Total Distance / Total Time)
    - Threshold = 12 ft. /min. / Objective = 45 ft. /min.
    - Vertical distance traveled must be minimum of 60 ft. with maximum of 90 ft.
    - Must have 4 climbers – Department of Defense contract personnel

- Dimensions – Threshold is 3.0 $ft.^3$, Objective is 1.0 $ft.^3$
    - Solution weight – Threshold is 20 lbs., Objective is 5 lbs.
- Subjective Requirements for System:
    - Must be easy to operate
    - Must be able to adapt to different environments
    - Must be stealthy (low noise, low visibility, untraceable, etc.)
    - Innovation/elegance/craftsmanship in design

6.2 Main Structure Subassembly:

- Functional
    - Should be able to maneuver up an even or uneven obstacle
- Performance
    - Can hold a load of 300 lbs. applied at an angle of 15˚ from vertical

6.3 Rotational Subassembly:

- Functional
    - Should be able to adjust the angle of the main structure relative to the wall
- Performance
    - Can hold a load of 300 lbs. applied at an angle up to 15˚ from vertical

6.4 Wall Plate Subassembly:

- Functional
    - Must support weight of climber, main structure, and ratchet sub assembly

- Performance
  - Will not shear or pull out when the moment due to a load of 300 lbs. applied at an angle of 15˚ from vertical

6.5 Secondary Device Subassembly:

- Functional
  - Should be able to lift remaining Airmen weighing 300 lbs. each
- Performance
  - Have the ability to ascend at a speed of 45 ft./min

6.6 Carrying and Organizing Gear:

- Functional
  - Must allow easy access to tools when needed
- Performance
  - Can safely secure all tools and allow for hands free option

7.0 Concept of Operations:

Time ordered sequence of events:

Step 1: Assemble the device (Figure 30)

Step 2: Install the first wall plate and insert the bottom rotational unit into square tube on wall plate (Figure 31)

Step 3: Rotate device upwards and ascend device (Figure 32)

Step 4: Install new wall plate and clip on to it (Figure 33)

Step 5: Raise the device vertically and insert the bottom rotational unit into square tube on wall plate (Figure 34)

Step 6: Ascend the device (Figure 35)

Step 7: Repeat steps 4 through 6 until the top of the obstacle is reached

Step 8: Install fixed line at the top of obstacle (Figure 36)

Step 9: Remaining Airmen ascend the fixed line using Atlas Fast Ascender device (Figure 37)

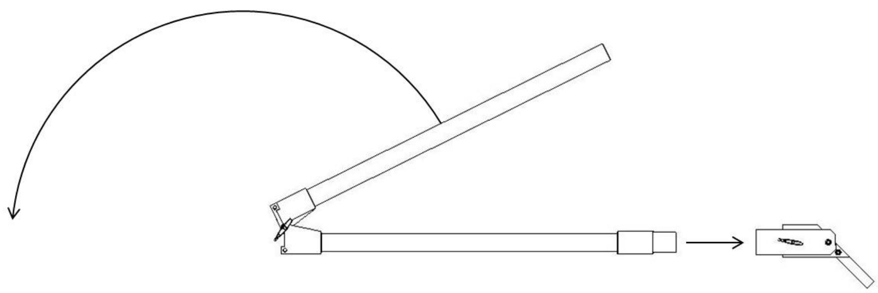


Figure 30 - Step 1

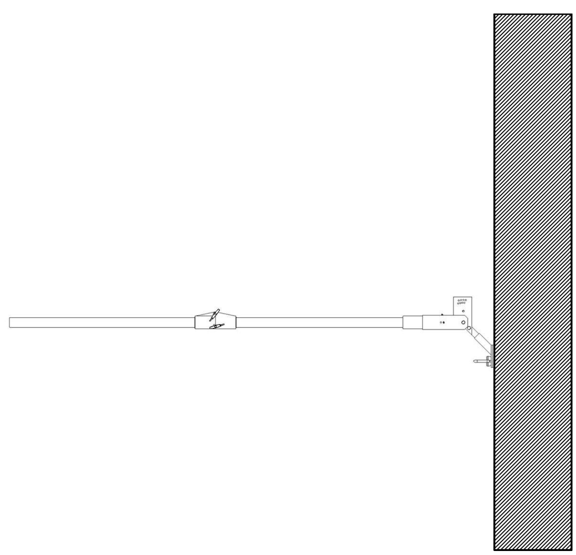


Figure 31 - Step 2

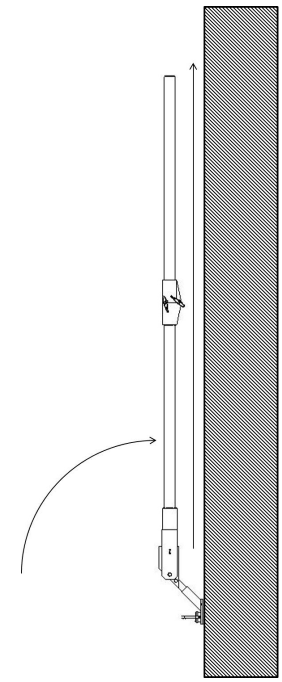


Figure 32 - Step 3

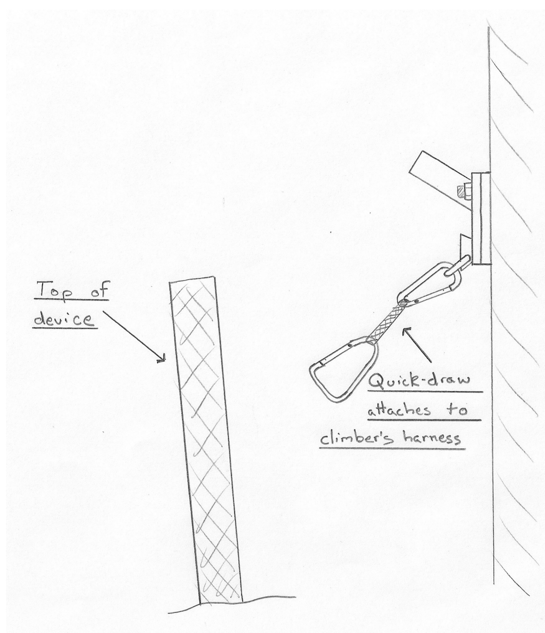


Figure 33 - Step 4

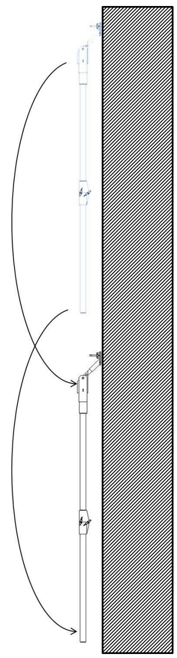


Figure 34 - Step 5

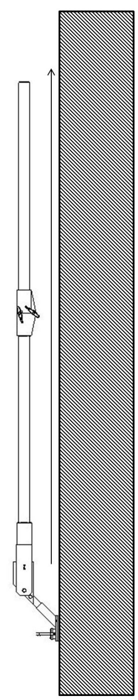


Figure 35 - Step 6

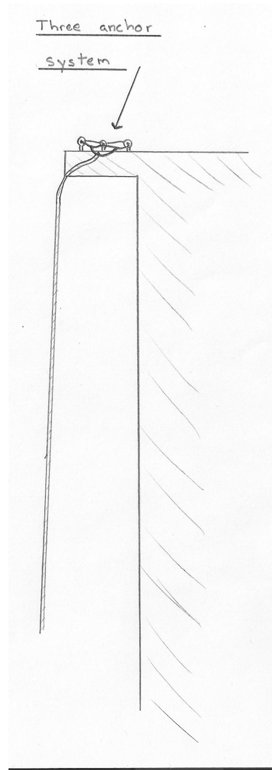


Figure 36 - Step 8

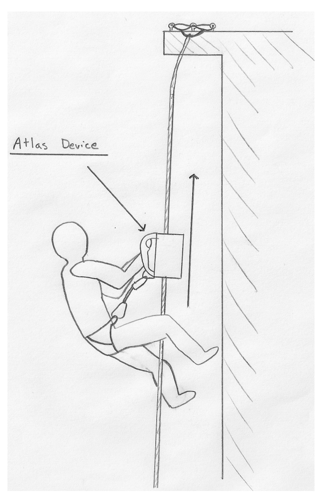


Figure 37 - Step 9

8.0 Verify and Validate:

Calculations, ANSYS, and prototype testing were performed to verify that the device has been built to meet all the requirements and targets as best as possible. The details of the analysis performed on each subassembly are included in the subassembly subsections of this report. The subassembly subsections can be found in the architectural design development section.

The first prototype for the climbing device was assembled and taken to the Auburn University Rappel Tower for testing. A validation test was performed on the device by simulating its operating conditions through one full revolution. This initial test revealed many problems in our design. It was found that the device is overweight, difficult to rotate, and leaned both laterally and longitudinally.

Once the issues discovered during the testing of the first prototype were resolved, we developed a new prototype utilizing the changes found in the subassembly subsections of the architectural design development section. This prototype was tested at a natural cliff location near Lake Martin to validate the new design and concept of operation. A few minor improvements were made after testing to refine our design. The prototype will continue to be refined until we depart for the competition.

9.0 Interfaces:

The interfaces between components of this device are mechanical interfaces. The specific details of each interface are listed below:

9.1 Wall - Wall Plate:

The wall plates are connected to the climbing surface by two 3/8” x 2¾” climbing grade expansion bolts (Figure 38). Holes will be drilled into the wall

using a hammer drill. Then, bolts will be bolted into the climbing surface. The wall plate incorporates two 1/2” holes to allow the bolts to pass thru and be secured with two nuts. The last climber to ascend the wall will remove the plates.

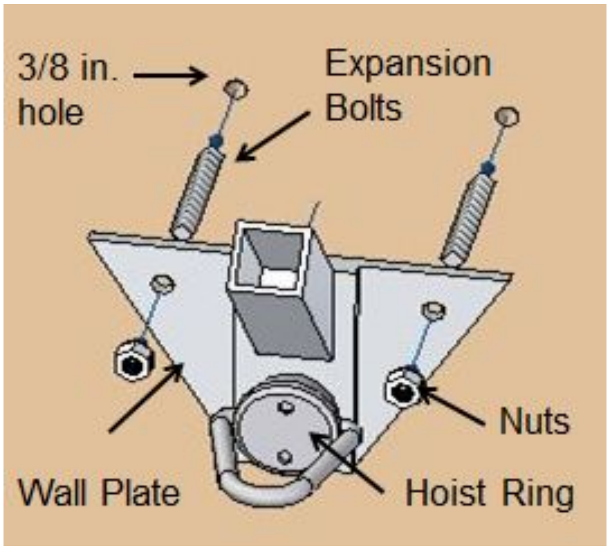


Figure 38 - Wall Plate Interfaces

9.2 Wall Plate – Climber:

The climber connects to the wall plate when raising the coupling and main structure. The climber’s weight needs to be removed from the segments in order to lift the main structure. This is accomplished by providing an anchor point on the wall plate (Figure 38). The operator will clip into the hoist ring on the wall plate using quick draws, raise the coupling and main structure and continue the climb.

9.3 Wall Plate – Rotational Unit:

The wall plates support the rotational unit. The wall plate will provide support by inserting the 1” x 1” extruded aluminum stock from the rotational unit into the square tube of the wall plate (Figure 39).

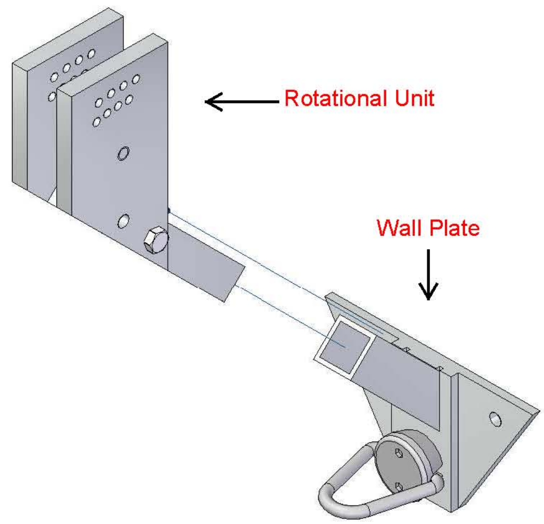


Figure 39 - Wall Plate Rotational Unit Interface

9.4 Rotational Unit – Coupling:

The 1” x 1” bar fits into the wall plate and is connected to the rotational unit. The rotational unit is inserted into the coupling and held together by a pivot bolt (Figure 40). The desired degree of the coupling can be adjusted for the environment, and is held in place by a pushpin.

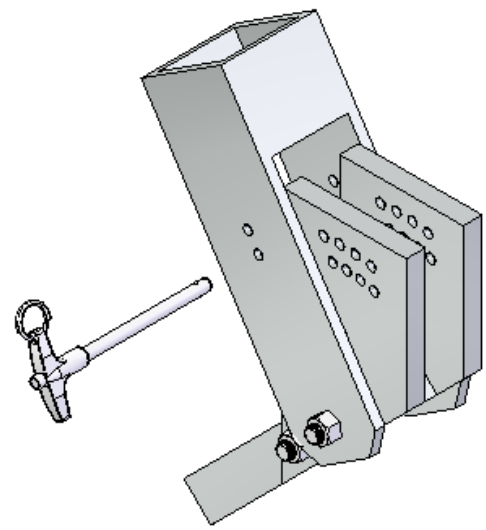


Figure 40 - Coupling and Rotational Unit Interface

9.5 Coupling – Climber:

A U-Bolt will be placed on the top of the climbing device to provide a fall protection system for the climber. The exact location of this anchor was determined during prototype testing to ensure that the fall protection system does not interfere with the climber's motion.

9.6 Rotational Unit - Main Structure:

The coupling and main structure are connected by inserting the main structure into the circular section connecting to the rotational unit. The assemblies are then pinned together with push button pins that pass through holes in both assemblies (Figure 41).

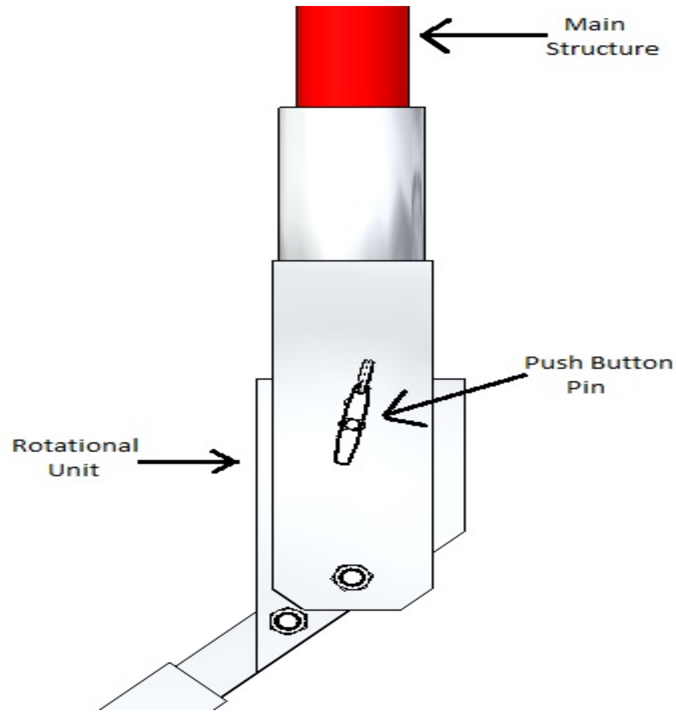


Figure 41 – Rotational Unit and Main Structure

9.7 Foot Pegs - Climber

The main structure is outfitted with two foot pegs per segment on alternating sides. These pegs allow the operator to climb the device. The pegs are held in place by a rubber sleeve, which is wrapped around the device and secured by shaft collars (Figure 42).

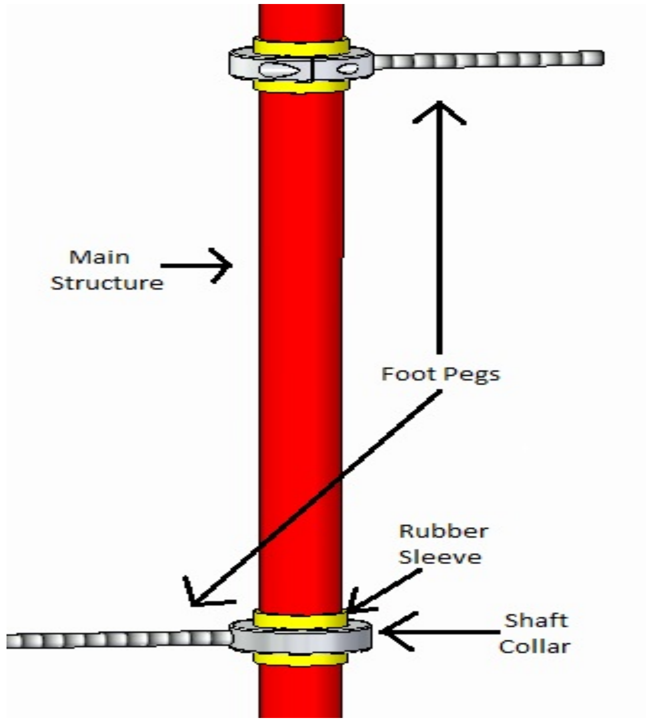


Figure 42 - Foot Peg Interfaces

9.8 Carrying Gear-Climber

All gear will be connected to the climber using the climber's harness. The wall plates will be connected two at a time using five carabiner-like devices. The nuts, bolts, and wrench will be located in a bag with a draw string to allow the climber to easily open and close the bag when necessary. The drill will be connected using a spring cord with carabiners located on both ends in order to access the drill when needed.

10.0 Mission Environment:

The mission environment for the Portable Ascent Device is one of the most undefined parts about the overall mission. One of the crucial aspects of having a good design is building adaptability into the ascent device. The

environment can vary from urban settings to cliffs in a desert. The device will be used indoors and outdoors, and will subsequently be exposed to dust, extreme high and low temperatures, and moisture. The ascent device must be able to operate under a range of conditions safely.

The characteristics of the ascent surface are also unknown variables. The height will be at most 90 ft. The surface may be made of any climbable material including rock, brick, or adobe. Since the material of the climbing surface is unknown, an anchor that can adapt to any surface is required. Another variable is that of multiple pitches. No specifics are given, because there are no specifics in the real life applications in which the ascent device may be deployed. There may also be an overhang, requiring some maneuvering away from the wall to clear the obstacle.

An example of an obstacle one might encounter with intent to use the device will be observed during the design competition. The obstacle is a 90 ft. vertical silo with an approximately 3 ft. overhang (Figure 43). The material of the surface is concrete, which is a respectable material for the drill bit and the anchors that will be used. However, the concrete contains re-bar, so the user will have to be mindful of the placement of the anchor holes and the depth.

Figure 43 - Obstacle in Competition

The bottom line is that the ascender device must be rugged enough to handle adverse outdoor conditions, and adaptable enough to overcome unknown barriers. The primary knowledge of the mission environment is that it is unknown. The Portable Ascent Device must incorporate adaptability into its design from the conceptual phase to verifying and validating prototype sub-systems.

11.0 Risk Management:

In order to evaluate the risk encountered at each stage of operation we used a system similar to the Risk Matrix that was supplied by the AFRL.

11.1 Transport and Assembly

Risk Modes: Very little danger to Airmen because they are on ground level.

Risk Mitigation: None required until Airman begins ascent. Airman must attach safety harness and get belay system set up before next steps.

Risk Assessment: None

11.2 Device Ascent

Risk Modes: After device is locked in vertical position, the Airman climbs to the top of the device. Slipping on the footholds will result in a fall to the height of the anchor plate (maximum distance: 9 feet). Failure of coupling at this point would result in a similar fall.

Risk Mitigation: Regardless of failure mode, maximum fall while climbing the device would be the distance from the climber to the bottom anchor plate. This maximum fall is within the safety factor of the rope and safety equipment. Testing will be necessary to prove that the anchor system is adequate as well. The footholds attached to the outside of the device will have non-slip material on them, lessening chances of falls. It is recommended that the Airman keep both hands gripping the device while ascending. An additional safety factor may be added by looping a quick draw around the device before beginning ascent. This would allow the Airman to lean out from the device, and would lessen the fall distance by catching on the footholds. The locking mechanism on the ratchet will prevent the device from swinging free.

Risk Assessment: Moderate

11.3 Anchor Plate Installation

Risk Modes: At this point, the Airman will be located near the top of the device. The Airman is now at the maximum fall distance, and must use at least one hand to drill into the surface of the barrier. Since the Airman is static, it is possible to alleviate much of the risk associated with this drilling and installation process.

Risk Mitigation: A quick draw will couple the climber to a bracket near the top of the device. This will allow the Airman to free hang from the device and use both

hands to install the next anchor plate. If the Airman loses footing while drilling, the resulting fall will be merely inches in height. It is recommended that the Airman retain footholds with both feet, while using the quick draw attach point as a support for the upper body alone. This will permit full range of motion, but minimize the stress on the bracket. The worst-case scenario would be if the quick draw fails or the Airman slips before attachment. This would result in a roughly 9 ft. fall before the belay system prevented the Airman from falling for the entire height of the barrier. However, this backup system would prevent serious injury in the case of massive device failure at peak height.

Risk Assessment: Low

11.4 Attachment to Top Wall Plate

Risk Modes: The Airman must disengage from the device and attach to the top wall plate in order to continue operation of the device. Because the Airman is 'resetting' the primary safety point, care must be given to ensure that a device failure at this point will not result in a serious fall.

Risk Mitigation: The Airman will attach to the newly placed anchor plate with a quick draw and then run the belay line through the attach point on the anchor plate. This effectively resets the safety system for the Airman. Maximum fall distance is now measured from this anchor plate. Once the primary safety system has been properly attached and tested, the Airman may now detach the quick draws from both the top of the device and the anchor plate.

Risk Assessment: Low

11.5 Device Coupling

Risk Modes: The Airman must disengage the bottom attach point of the device and attach the top to the newly installed anchor plate. Then, the Airman must raise the main structure to the new wall plate. The Airman is free hanging from the anchor plate at this point.

Risk Mitigation: The primary belay system attaches the Airman to the anchor plate. All operation during these steps occurs with the Airman directly hanging from the plate. A quick draw attached to the anchor plate could add an additional level of safety, but the overall safety of the climber is as high as it can ever be while midway up the barrier itself. The worst-case scenario of the wall plate completely failing would result in large full. This type of failure is highly unlikely because the anchor plate will be designed with a high safety factor.

Risk Assessment: Very Low

11.6 Secondary Ascent using Power Ascenders

Risk Modes: The Airman who operates the device will install a 3-anchor system at the top of the barrier, and the rest of the squad shall reach the top by use of power ascenders. The climbers will completely bypass the wall plates, using a belay rope hanging from the 3-anchor system. Since there is no intermediate safety system, extra caution must be given that the belay system does not fail.

Risk Mitigation: The rope is looped through the belay device on the safety harness of each Airman. Each of the three anchors at the top of the barrier is capable of supporting the load independently. An equalizer ensures that the load is distributed equally to each anchor. This method of ascent is in common practice and is considered to be one of the safest possible climbing methods.

Risk Assessment: Very Low

12.0 Project Management:

The Air Force Research Lab Design Challenge team differed from the typical project team, in that the Industrial Sponsors are not immediately available to provide feedback in person. To combat this disadvantage, two additional people have attended presentations and made themselves available to field questions as well as provide guiding advice. These personnel consist of Dr. Madsen, Ph.D. Mechanics and Hydraulics, and Michael Cahill, US Army technical expert.

The design team is structured to include a professor, teaching assistant, manager, systems engineer, financial assistant, scribe, and team members. A visual breakdown of the team structure along with personnel responsible for collateral duties is shown in figure 44. Each team member was assigned a primary concentration to allow focus on a particular portion of the project. Additionally, each member was responsible for minor tasks to assist with the project manufacturing process. The primary and minor assignments are shown in table 8.

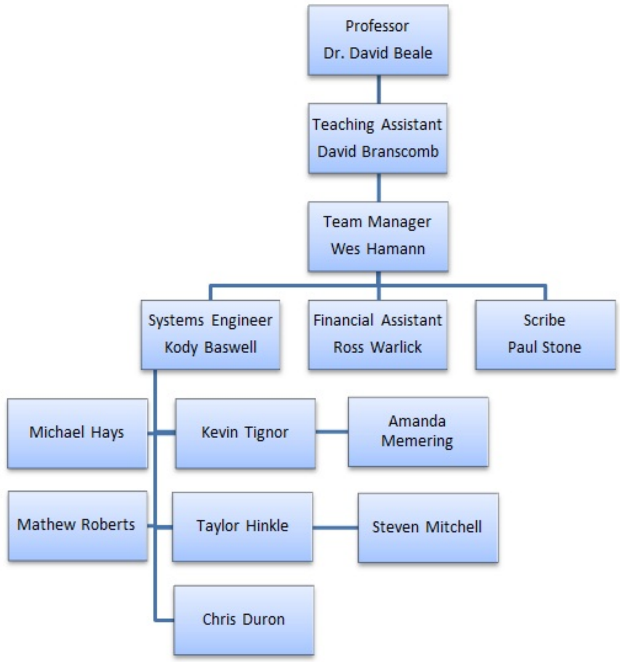


Figure 44 – Team Structure

Table 8 - Personal Assignments:

Member	Primary Concentration	Minor
Wesley Hamann	• Management	• N/A
Ross Warlick	• Ascension of main structure	• Budget • Machining
Michael Hays	• Lightweight structures	• Safety • Machining
Kevin Tignor	• Lightweight structures • Initial ratchet design	• Paint • Machining
Amanda Memering	• Lightweight structures	• Climber configuration
Steven Mitchell	• Initial ratchet design	• Lightweight structure optimization • Machining
Paul Stone	• Lightweight Structures	• Scribe • Secondary ascent
Matthew Roberts	• Ratchet replacement design • Wall-plate design	• Machining
Taylor Hinkle	• Anchors	• Fall protection • Machining

Evan Hallmark	• Wall-plate optimization (weld)	• Machining
Chris Duron	• Lightweight Structures	• Machining • Structural testing
Kody Baswell	• Systems engineer	• Machining

13.0 Conclusion:

Our team has worked to accomplish all mission objectives and reach all target goals set up for the project. While doing this, we have also worked to keep our design safe, simple to understand, and easy to operate. The reason for this is because the end user, the Airmen, do not require an overly intricate device. The Airmen who will be operating the device are looking for a device that is easy to utilize and can get them to the top in a safe, timely, and reliable manner.

Through thorough testing and mathematical analyses, the original concept has been refined into a working prototype that has undergone significant testing. Based on the results of those tests, the prototype has been refined and optimized to meet our need. Through this process we hope to achieve all target values while maintaining the core values of safety, simplicity, and ease of use.

Overall, the project is on time will be ready for the Air Force competition at the end of April. Both our corporate and faculty sponsors have played an essential role in the project and have continually assisted the group in reaching their full potential. The project has given every member of the group a great opportunity to further their engineering knowledge and skills.

PORTABLE SPANNING DEVICE
TECHNICAL REPORT

By:
Senior Design Group Corp 1: Air Force

A report submitted in partial fulfillment
of the requirements for

2013 AFRL University Design Challenge and MECH 4250

Department of Mechanical Engineering

Auburn University

04/08/2013

ABSTRACT

The Air Force Bridge Project is a seemingly simple problem with unlimited solutions. The objectives of this project include the designing, testing, and manufacturing of a lightweight, portable device that allows military personnel to safely traverse a horizontal void (ravine, river, stream, gap between rooftops, etc.) Pararescuemen are United States Air Force Special Operations Command operatives tasked with the recovery of important equipment and, in certain cases, the medical treatment of personnel. Their missions charge operators with saving the lives of aircrews involved in aircraft disasters, accidents, or crash landings away from air bases, meaning they are required to traverse a multitude of different environments. These environments have the potential to be relatively smooth, allowing for straightforward transition of the teams from point "A" to point "B", but that is often not the case.
Situations can arise in which relatively large gaps within the geography of a region must be crossed. In order to resolve this issue, the design team has rendered multiple concepts for Air Force Special Operations teams to allow them to traverse themselves, along with their equipment, across a gap spanning 20ft. These concepts are lightweight in design, easily packaged occupying less than 5 ft^3, quickly deployable and retrievable in less than 5 min. These devices will not only allow the teams to traverse the gap, but to do so quickly, quietly, and in an effective manner as to add proficiency to the task of mission completeness.

TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

ACKNOWLEDGEMENTS

On behalf of the Auburn University Mechanical Engineering Department, we would like to thank our sponsors Michael Cahill and Dr. Nels Madsen for your contribution in the Senior Design Competition AFRL Challenge. We would also like to send an extended thanks to TCR Composites for generous contributions of carbon fiber tow used in the creation of structures. Additional thanks to technical advisor, Dr. David Branscomb, whose work in carbon fiber open structures paved the way for many subsystems of the device. Finally, an extended thanks to technical advisors and current graduate students Nakul Kothari and Ross Warlick for their insight and administrative aid.

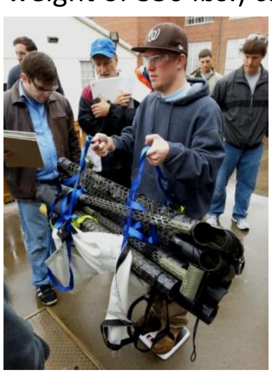
INTRODUCTION

United States Air Force Special Tactics Battlefield Airmen executing rescue and assault operations around the world have experienced difficulty traversing many different types of gaps. Some forms of these gaps include irrigation canals, moving from one rooftop to another, crossing minefields, fast flowing mountain streams, snow and glacier crevasses, desert rock formations, unstable/collapsed structures, and compound walls. These obstacles often range from one to twenty feet in width, and often have landings at different elevations. Ground forces need an easily portable, lightweight, multipurpose tool to negotiate these obstacles.

Battlefield Airmen often have to wear body armor and carry a lot of gear for their missions, along with any heavy equipment or injured soldiers they may have to carry or assist. This cumbersome load makes it impossible to simply jump over every obstacle. Fording canals and streams is often undesirable while loaded with gear and/or injured personnel, especially when there is risk of heavy currents and/or unknown depths.

Pre-mission intelligence reports may advise soldiers of the terrain that lies before them. One current solution to this problem is to carry large aluminum ladders with them for missions that include large gap crossings. These prove to be bulky, heavy, and cumbersome additions to what is already a sizeable load of standard and mission-specific equipment.

These airmen need a more reliable way to cross any aforementioned gap encountered on a given mission. Solutions to this problem should be lightweight, have a multipurpose role (could be used for something other than a bridge), be easy to deploy (i.e. while wearing winter or tactical gloves), reusable, and easy to maintain (e.g. field repairable). It needs to be reliable, strong, and stable, so a soldier weighted down with gear or possibly carrying an injured person (i.e. total weight of 350 lbs.) can safely traverse the obstacle.



PROJECT MANAGEMENT:

The project manager of the Air Force Portable Spanning Device Prototype design serves as the primary decision maker and spokesperson between the overlord, sponsors, faculty and the design team. He also delegates tasks known as contracts of deliverables, keeps track of the team's schedule, and works out logistics of the competition. Corp 1's management structure is shown below.

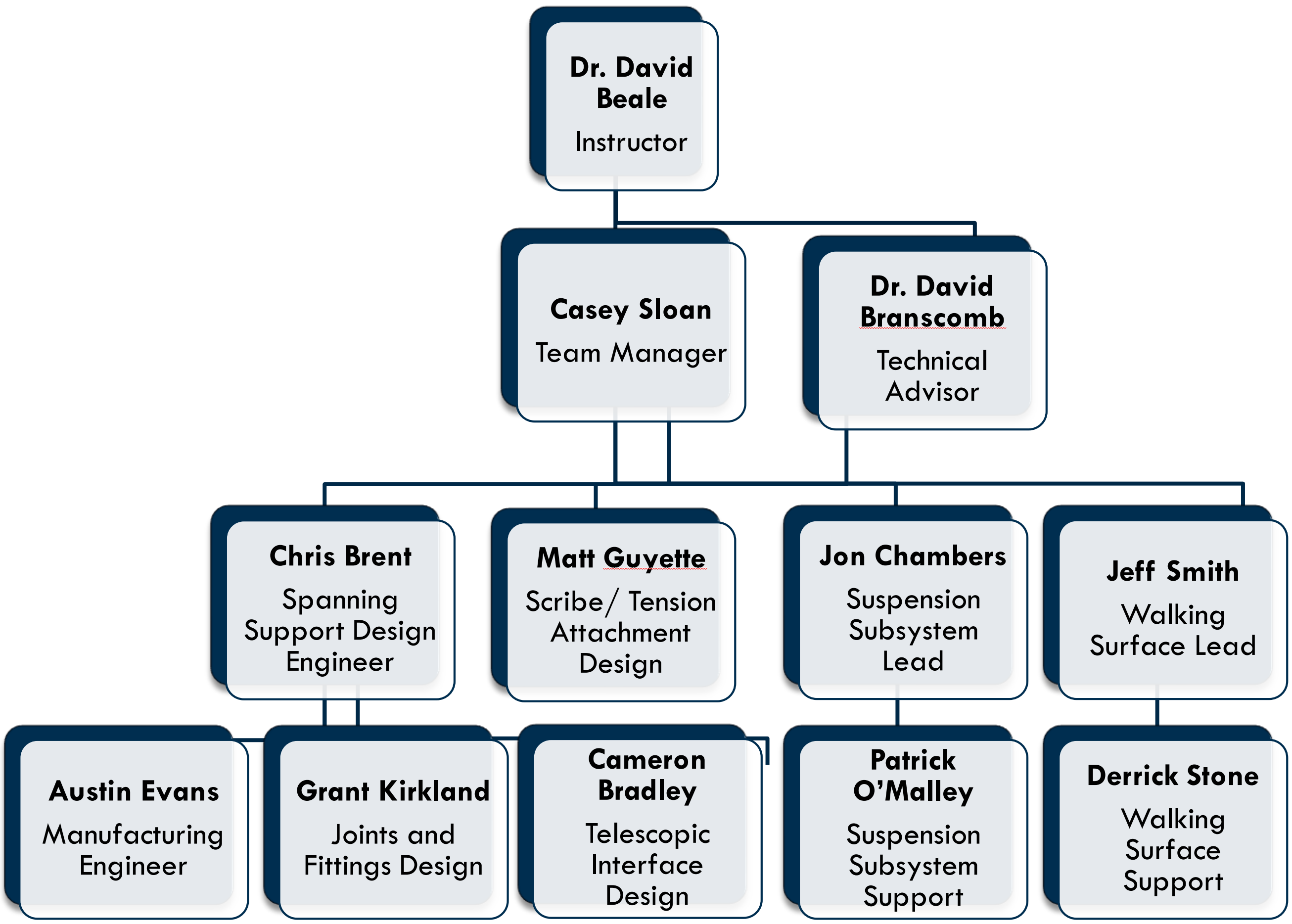


Figure 1: Management Structure

SYSTEMS ENGINEERING

Systems engineering (SE) is the engineering process used to create a system. It is based on concurrent engineering and incorporates the engineering design process. Corp 1 has previously gone through Pre-Phase A (Concept Studies), Phase A (Concept and Technology Development),

Phase B (Producing a Preliminary Design), Phase C (Detailed Design) and is currently in Phase D (System Assembly Integration, Test and Launch).

MISSION OBJECTIVE

Design a compact, lightweight, portable system that enables military ground forces to safely traverse a 5-20 ft. gap with their equipment and rescued personnel.

CUSTOMER'S NEEDS AND DESIRES

Air Force Pararescuemen, also known as PJ’s, are highly trained special forces personnel whose main tasks are to:

- conduct combat search and rescue operations
- recover downed aircrews and aerospace hardware
- provide medical treatment when needed (emergency paramedic qualified)

Often times, these missions are conducted behind enemy lines in groups of as little as two PJ’s. Therefore, their missions are often done as quietly and quickly as possible. In a mission, they can come across a vast number of situations and conditions. Some of their working environments include: arctic, jungle, mountains, desert, urban, and wet environments.

Obstacles they could face include large gaps, steep inclines, large objects/structures, and other combinations of difficult terrain.

Currently, PJ’s are rather limited with conquering some of these obstacles, mostly due to the fact that they are limited to using only what they can carry with them. Due to their many job functions, PJ’s carry a lot of weight in/on their rucksacks yet must maintain required agility and mobility.

CUSTOMER'S GOALS AND RESULTING SPECIFICATIONS

Figure 2: Portable Spanning Device (PSD)

Table 1: Product Specifications

Requirements	Goal	Specification	Units
Static Load	350	350 plus	lb
Span	5-20	15	ft
Weight	5-20	26	lb
Volume	1-5	4.9	ft^3
Set Up Time	Not Specified	5 - 6	min
Cross Time	Not Specified	15	sec
Surface Elevation	0	(+-15)	Degrees

PSD CONCEPT OF OPERATIONS

Unpack

- Separate the bundle by loosening the tension straps and disperse each subsection into their respective locations.
- Telescope each Dragon Plate tube and insert pin to ensure fixed length of ~6 feet.
- Two modules should be placed on either side of each tee.
- Place the modules end to end on either side of the tee.

Assemble

- Telescope each Dragon Plate tube and insert pin to ensure fixed length of ~6 feet.
- Telescope each smaller tube through the larger one and insert pin to maintain length.
- Insert each module into other module and insert pin.
- Insert each larger module into the corresponding part of the tee section
- Attach two separator cars at the indicated position on the vertical supports.
- Attach the separator bars with footings to each end
- Attach the tension straps and tension cable choke straps to the outside of the separator bar
- Attach tension cable to both sides
- Apply proper tension using the ratchet device

Deploy and Inspect

- Make sure the vertical support is perpendicular to the horizontal device
- Grab the parachute cord and brace for lowering
- Stand device upright and lower slowly and under control
- Assess the device once lowered into the gap and make sure everything looks as designed.

Figure 3: CON OPS

PSD CAD MODEL AND BOM

Figure 4: PSD CAD MODEL

Table 3: BOM

Item	Part #	Description	Weight lb	QTY	Material	Est. Cost
1		Telescope Section, End	1.02	4	CF	
2		Telescope Section A, Inner	1.21	4	CF	
3		Telescope Section A, Outer	1.05	4	CF	
4		T Section	0.57	2	CF	
5		Vertical Support	0.51	2	CF	
6		End Cap	0.24	2	Plastic	
7		Tension Cables	0.57	2	Nylon	
8		Choke Strap	0.08	4	TBA	
9		Walking Surface	2	4	TBA	
10		Pins	0.04	8	CF	
11		Carabiner	0.05	TBA	Al	
12		Separator Bars	0.35	4	CF/KVLAR	
13		Velcro Straps	0.02	8	Velcro	
14		Deployment Cable	0.17	1	Nylon/Al	

SUBSYSTEMS

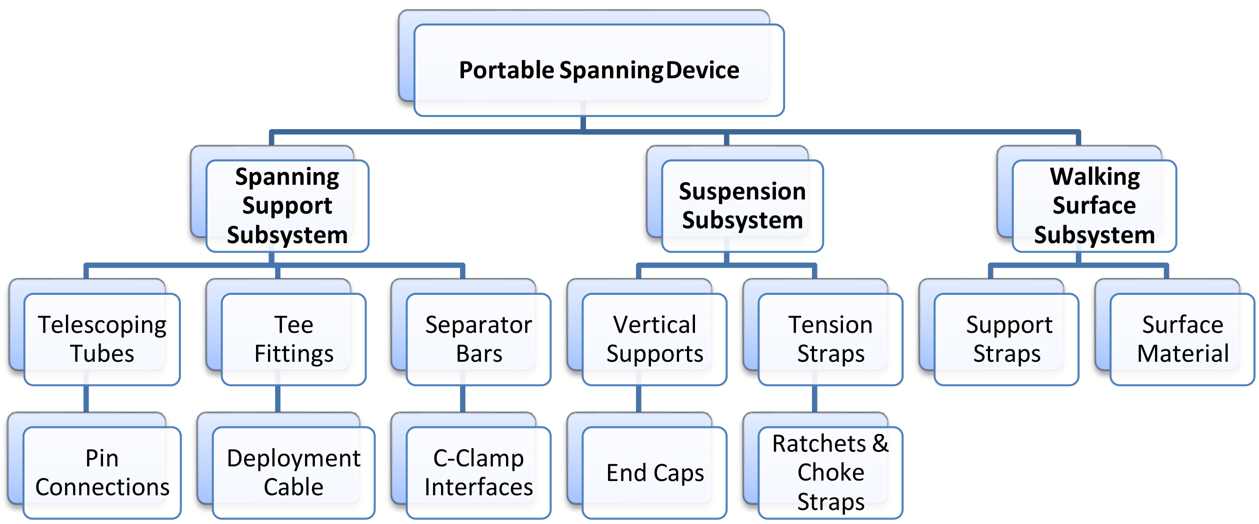


Figure 5: System Architecture

SUSPENSION SYSTEM

The suspension system is designed to reduce the maximum bending moment on the horizontal structure and consists of choke straps, tension cables, vertical support tubes and end caps.

The Choke Strap and Tension Cable

The choke strap is designed to attach the suspension cable to the horizontal tube and cinch down upon tightening. The strap provides a horizontal compressive force on the members and transfers the vertical load at the center of the structure to the ground at the ends of the structure.

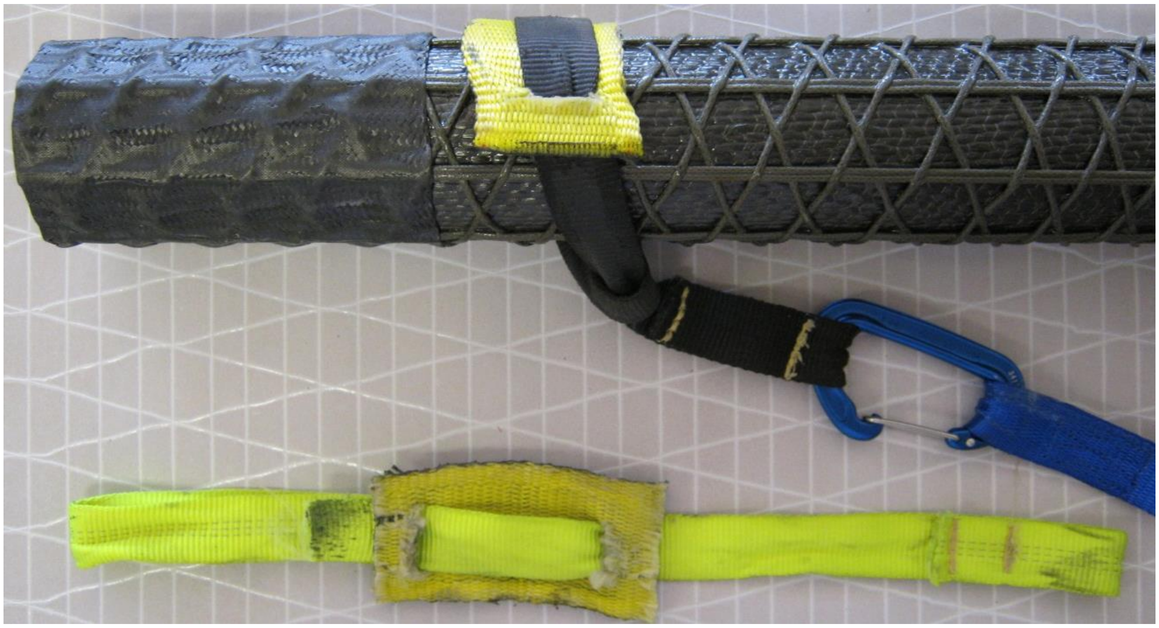


Figure 6: Choke Strap and Tension Cable

The End Cap

The End cap fits onto the vertical support such that the tension cable may be slid and held under the vertical support. Applying tension in the cable produces an upward force on the vertical open structure that works to counteract the moment caused by the 350-lb load.

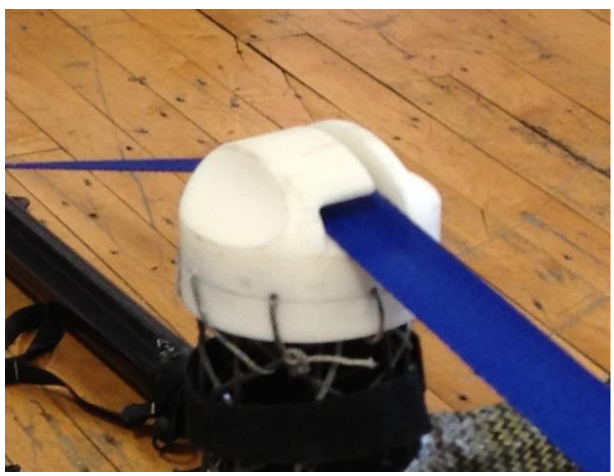


Figure 7: End Cap

SPANNING SUPPORT STRUCTURE

The spanning support structure consists of horizontal spanning members: the large diameter tubes, small diameter tubes, Tee section, separator bar, and interfaces between the members.

End Large Diameter Tube

This end support tube (below) was made at Auburn using unidirectional carbon fiber sleeves to provide bending strength, an outer open structure braid to provide stiffness and hoop strength, and vacuum sleeved ends to improve end joints.

Figure 8: Telescope Section, End

Small Diameter Tube

This telescoping tube section (below) was made using commercial 2 inch carbon fiber tubing with built up pre-impregnated and Kevlar ends in order to facilitate tight connection tolerances. Carbon Fiber guide tubes were also added to guide pins through the small tubes and decrease assembly time.

Figure 9: Telescope Section (Small Diameter)

Large Diameter Tubing

This center section (below) accepts the inner telescoping tube and is also off-the-shelf. It has internal unidirectional carbon fiber for bending strength with a twill outer layer for hoop strength.

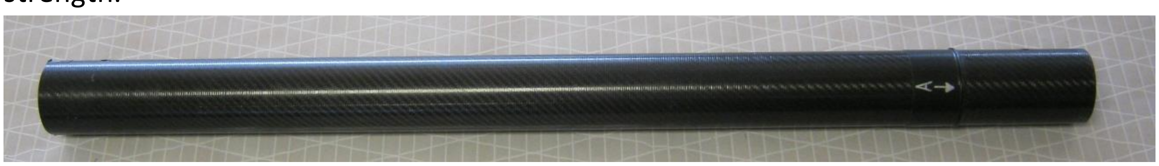


Figure 10: Telescope Section (Large Diameter)

T Section

This T section (below) was laid-up using carbon fiber prepreg woven fabric around a unidirectional core in order to provide the strength needed at the point of maximum bending moment without a substantial amount of added weight.

Figure 11: T Section

Separator Bar

The separator bars were made of carbon fiber open structures wrapped with Kevlar and carbon fiber braided jackets that serve as clamping points to the main structure.

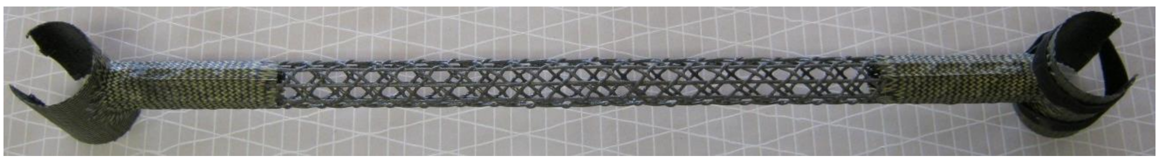


Figure 12: Separator Bar and Velcro Strap

Interfaces

Carbon fiber pins with tapered ends, elastic bands used for locking, and another elastic band used for attachment to the tube. The pins and corresponding guide tubes are used to secure the tubes together during assembly and use.

Figure 13: Pin and Guide Tube

Figure 14: Walking Surface

Figure 15: Carabiner

Figure 16: Deployment Cable

APPENDIX

CARBON FIBER STRUCTURE TESTING, ANALYSIS & DESIGN

Bending Testing, Carbon Fiber Open Structure

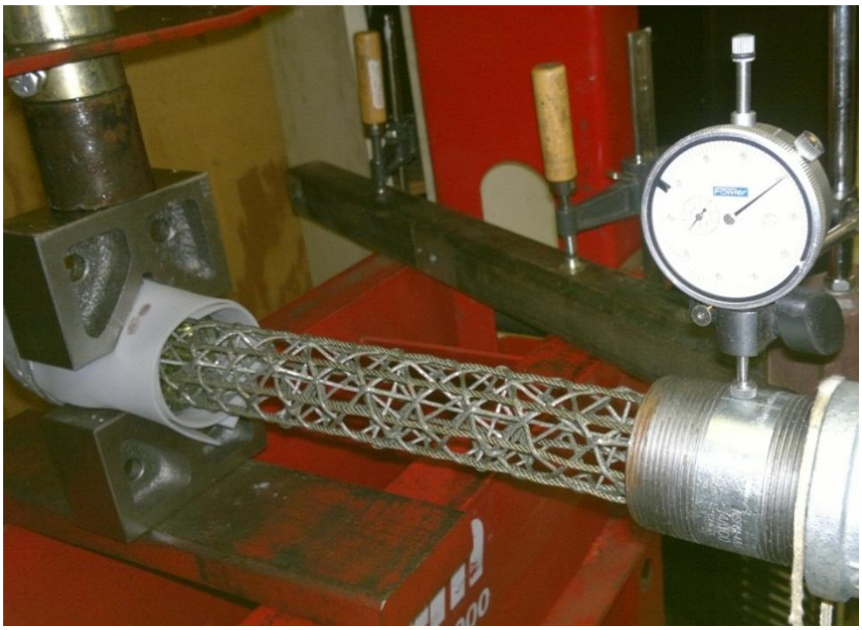


Figure 17: Bending Testing

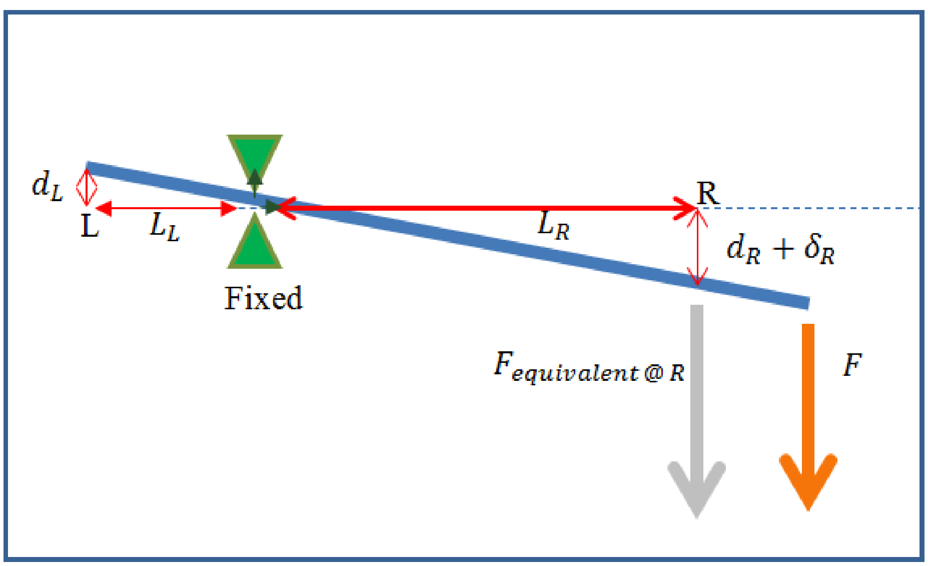


Figure 18: Cantilevered Beam Diagram

Table 4: Bending Test, Parameters

Distance to Application of Force	L	12.625	in	**0.321**	m
Distance to Take of Deflection	L_R	11.375	in	**0.289**	m
Distance to Take of Movement	L_L	4.300	in	**0.109**	
Area Moment of Inertia Max	I	0.048	in^4	**2.00E-08**	m^4
Radius of Tube	r	0.820	in	**0.021**	m
Cross Section Area	A	0.138	in^2	**8.87E-05**	m^2

The following outlines how deflection was determined from a cantilevered test which wasn't completely rigid.

$$\frac{d_L}{-L_L} = \frac{-d_R}{L_R} \rightarrow d_R = L_R \frac{d_L}{L_L} \qquad \textbf{[Eq. 1]}$$

where, d_L = vertical distance on left side between Neutral Axis and point measured

d_R = vertical distance on right side between Neutral Axis and point measured

L_L = horizontal distance on left side between fixed point and measured deflection

L_R = horizontal distance on right side between fixed point and measured deflection

$$d_{measured} = d_R + \delta \qquad \textbf{[Eq. 2]}$$

where, δ = bending deflection

$$\delta = d_{measured} - d_R \qquad \textbf{[Eq. 3]}$$

$$\delta = d_{measured} - L_R \frac{d_L}{L_L} \qquad \textbf{[Eq. 4]}$$

Table 5: Bending Test Data

FORCE (N)	Movement (dm) At R (in)	Movement (dL) At L (in)	DEFLECTION dm-dL(LR/LL) (m)	MOMENT (Nm)	Force at A (N) F_e=F*L / L_A	Max STRESS (GPa) Sigma=My / I	Bending Stiffness E*I= (-F*L^3)/(3*D)	Elastic Modulus (GPa)
115.24	0.1930	0.0180	0.0037	36.95	127.90	0.039	-278.46	-13.94
156.93	0.2760	0.0260	0.0053	50.32	174.18	0.052	-266.05	-13.32
186.68	0.3460	0.0360	0.0064	59.86	207.19	0.062	-261.52	-13.09
188.88	0.3610	0.0395	0.0065	60.57	209.63	0.063	-258.68	-12.95
197.72	0.3820	0.0430	0.0068	63.40	219.45	0.066	-258.93	-12.96
206.26	0.4010	0.0455	0.0071	66.14	228.92	0.069	-258.19	-12.92
215.07	0.4220	0.0485	0.0075	68.97	238.71	0.072	-257.25	-12.88
	0.0750	0.0290	0.0000	0.00	0.00	0.000	0.00	0.00
115.24			0.0000	36.95	127.90	0.039		0.00
156.93			0.0000	50.32	174.18	0.052		0.00
213.14	0.3610	0.0245	0.0075	68.35	236.57	0.071	-252.80	-12.65
215.34	0.3770	0.0265	0.0078	69.05	239.00	0.072	-246.50	-12.34
224.18	0.3980	0.0290	0.0082	71.89	248.82	0.075	-245.13	-12.27
232.72	0.4160	0.0315	0.0084	74.63	258.29	0.078	-245.75	-12.30
241.27	0.4450	0.0355	0.0089	77.37	267.78	0.081	-241.42	-12.08
250.09	0.4730	0.0405	0.0093	80.20	277.57	0.084	-240.13	-12.02
254.52	FAILURE			81.62	282.49	0.085		
							-254.68	-12.75

Compression Testing, Carbon Fiber Open Structure

Testing of the carbon fiber open structure in compression revealed ultimate compression strength of 86 MPa and Young's Modulus of 1.73 GPa.

Figure 19: Compression Test

Commercial Carbon Fiber Tube Testing

Due to the unavailability of a standard fixture, the setup of the Instron machine in the lab, the cost of testing commercial tubing to failure, and the time allowed for research and development, it was not feasible to do a three point bending test on the commercially available tubing. Instead a direct comparison was made between it and an equivalent open structure. In comparison, the commercial tubing was lighter, stiffer and stronger. This led to the use of the off-the-shelf tubing in the final design which was proof tested in the final build (see pg XX).

Carbon Fiber Failure Mode Analysis

Figure 20: Failure of Open Structure

Open structures loaded to failure fracture in the top axial yarns (fail in compression). These fail often with little assistance from the internal z truss. In one case an 18' section of the bridge was dynamically loaded by a 185 lb person. Although estimations based on assumed inputs at the time lead to a factor of safety around 1.5, it should be pointed out that these calculations assume optimum static conditions and ignored manufacturing defects.

Solid Works Analysis

Early analysis was done using Solid Works modeling software in order to determine the required thickness of carbon fiber tubing in the design based on the properties from the open structure test data. The figure below is a model of one quarter of the bridge which has been analyzed about the symmetric middle T section. The carbon fiber tubing has a thickness of .14" (or greater) and offers a factor of safety of 1.5 where the maximum stress experienced is near the center. This thickness of tubing was unacceptable because of its weight. The results of this analysis led to a search for a material with an ultimate bending stress greater than 85 MPa that still had a lower total weight.

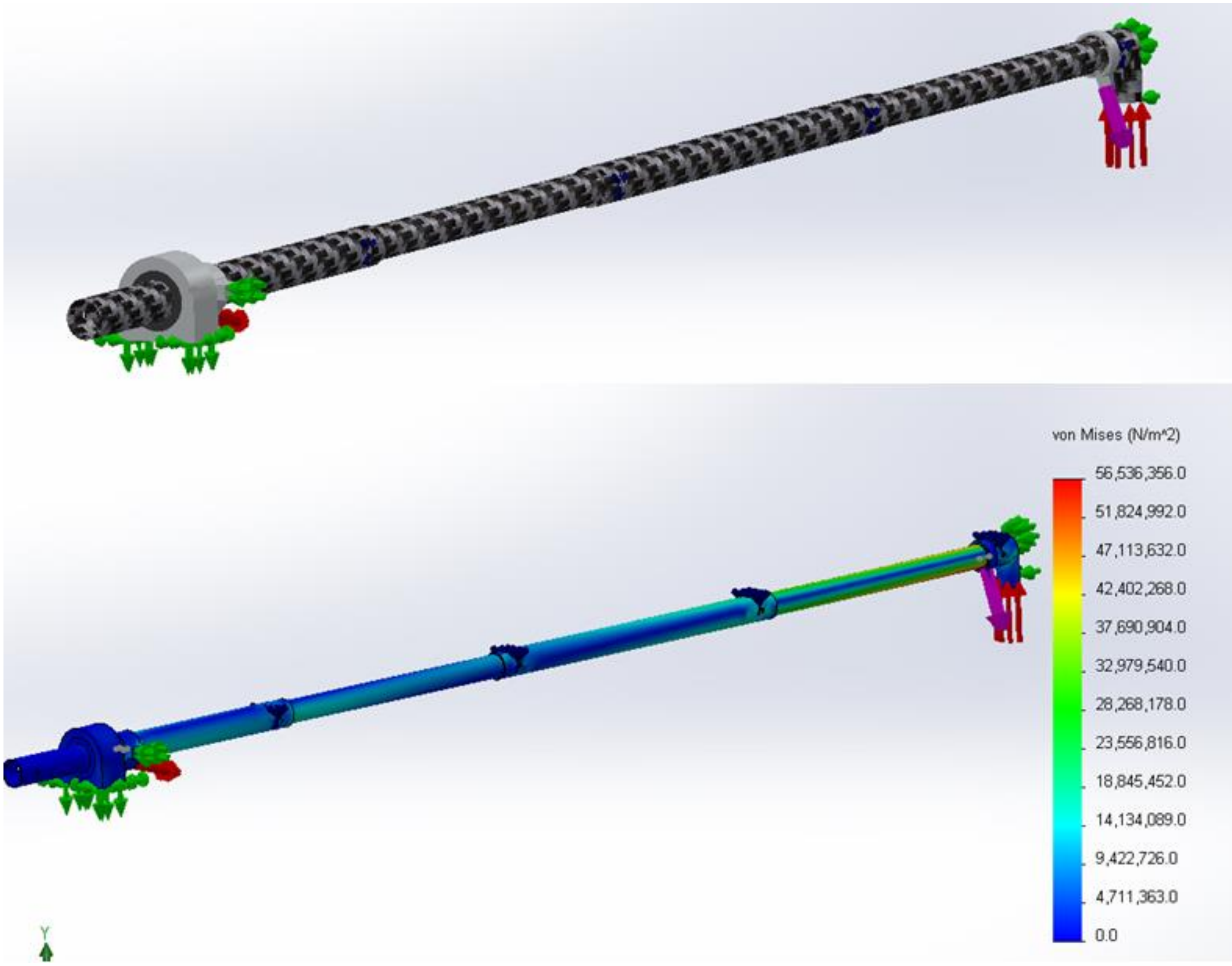


Figure 21: Solid Works CAD Simulation (1/4 Bridge, Mirrored)

ANSYS analysis

An ANSYS model was made of the entire bridge structure and divided into beam elements with varying cross sections and material properties of both 2024 T6 aluminum and carbon fiber. 2024 T6 aluminum has a much higher ultimate bending strength than carbon fiber and is better on a per weight basis. Below the ANSYS analysis of the structure has a maximum calculated deflection of only half an inch. Based on further research however it was decided not to incorporate T6 2024 aluminum into the design due to its poor fatigue limit which is well below the ultimate static bending strength after only a hundred cycles.

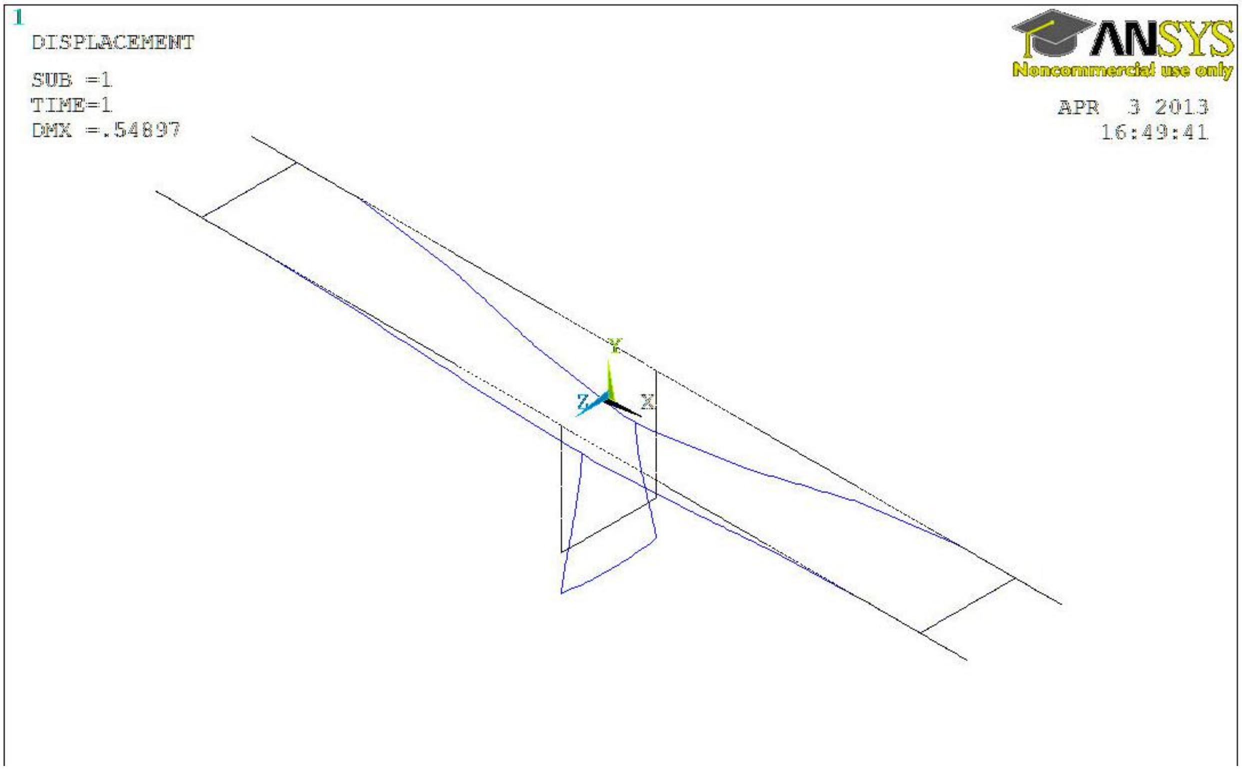


Figure 22: ANSYS model

Hand Calculations and MATLAB Coding Analysis

Final analysis was done by deriving the force and moment equations for the maximum load applied at the center of the beam. These equations were then utilized in MATLAB to solve for the maximum stress in each beam element based on the inputs given to the program such as the number and thickness of axial yarns in the open structure, tube diameter, and the number of carbon fiber jackets or sleeves added to the open structure. An example of the calculations and MATLAB code may be seen below. All parameters optimized in this design iteration were for Carbon Fiber Open Structures wrapped with sleeves. The optimized design showed increasing diameters up to 3 inches in addition to the thick sleeve would have made the structures heavier than the commercially available tubes. Due to the desire to cut down on weight and volume, this analysis led to the rejection of carbon fiber structures with sleeves on them near the center of the bridge and resulted in using 2 and 2.5 inch commercial tubing while reducing the gap to about 15.5 ft.

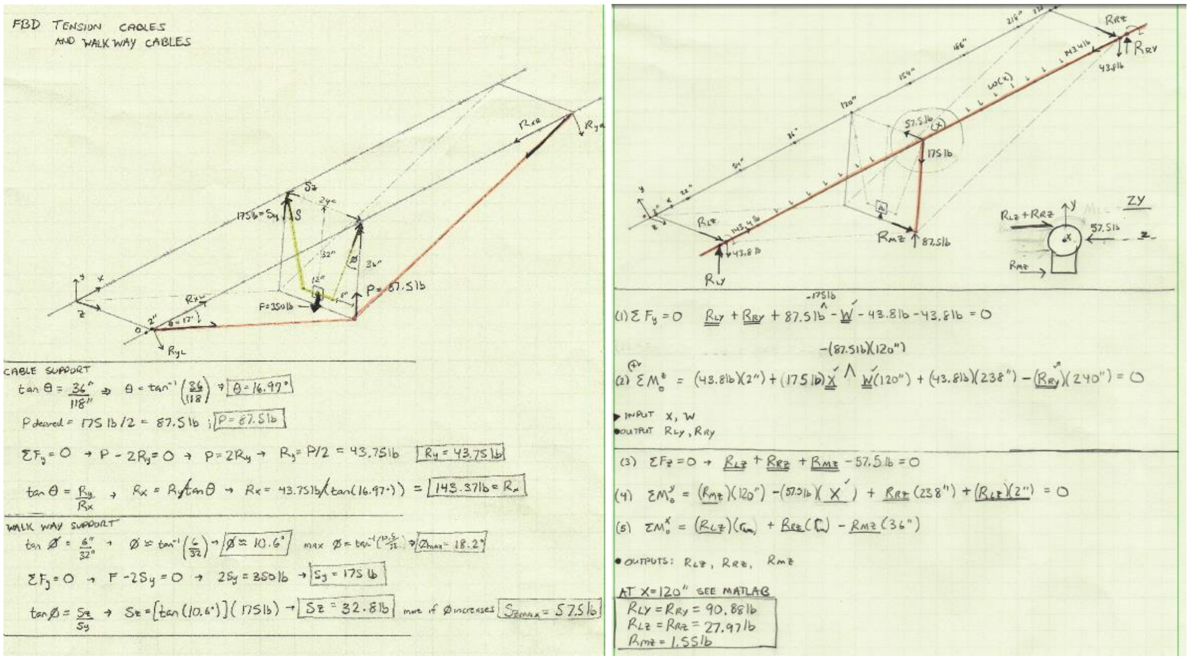
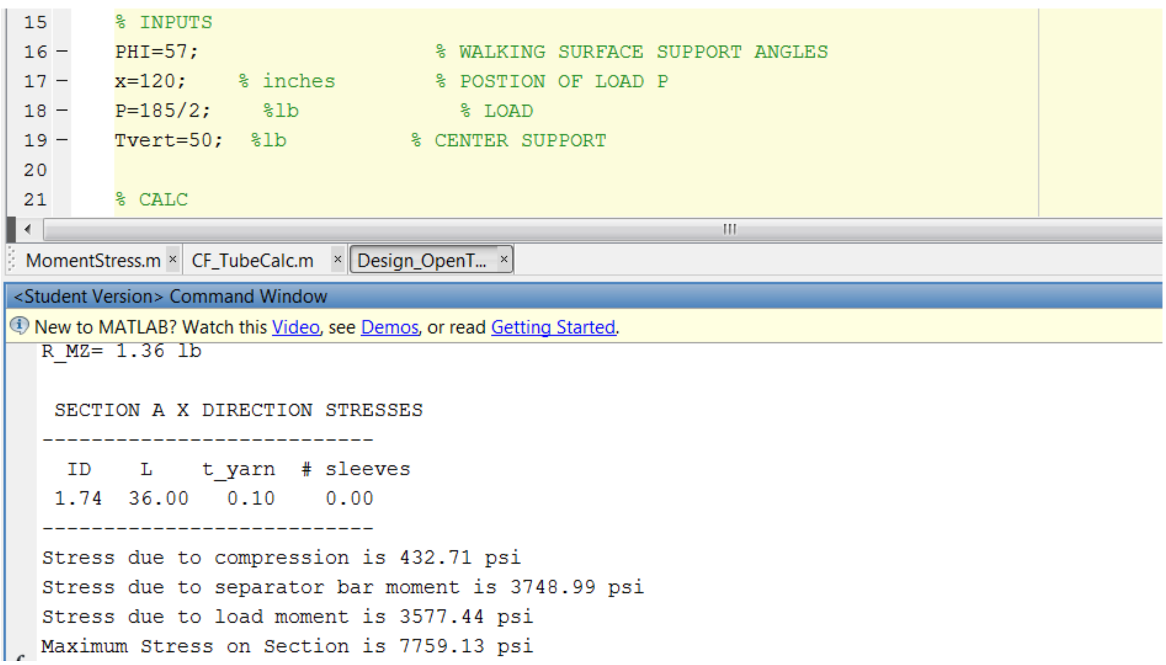


Figure 23: Hand Calculations



```
% INPUTS
PHI=57;                      % WALKING SURFACE SUPPORT ANGLES
x=120;     % inches          % POSTION OF LOAD P
P=185/2;    %lb                % LOAD
Tvert=50;  %lb             % CENTER SUPPORT

% CALC
```

MomentStress.m × CF_TubeCalc.m × Design_OpenT... ×

<Student Version> Command Window

New to MATLAB? Watch this Video, see Demos, or read Getting Started.

```
R_MZ= 1.36 lb

 SECTION A X DIRECTION STRESSES
---------------------------
  ID     L     t_yarn   # sleeves
 1.74   36.00   0.10     0.00
---------------------------
Stress due to compression is 432.71 psi
Stress due to separator bar moment is 3748.99 psi
Stress due to load moment is 3577.44 psi
Maximum Stress on Section is 7759.13 psi
```

Figure 24: MATLAB Code

Prototype Testing: Proof Loading

The structure was proof loaded to 355lb at 15 ft to show that it could support the required load.

Figure 25: Proof Loading Structure to 350 lb

Manufacturing Method

The process of manufacturing carbon fiber open structures consist of three steps: yarn fabrication, open structure braiding, and curing.

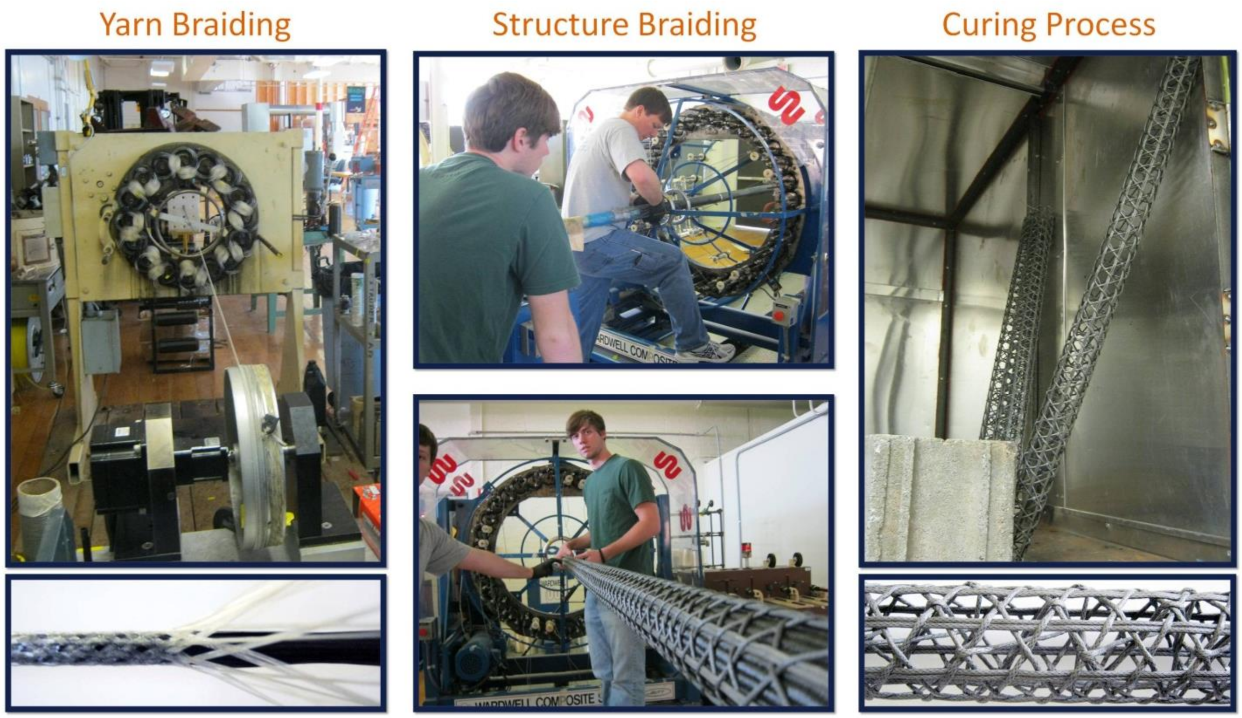


Figure 26: Manufacturing Process for Carbon Fiber Open Structures

The first step in the process is yarn fabrication. Yarns are fabricated from sticky ribbons of carbon fiber with resin in them (prepreg tow) and a jacket of Vectran strands. According to the 1995 book *Carbon Fibers* by Peebles, the carbon fiber is a polymer which has been, "through an expensive process involving three different steps: stabilization, carbonization, and high temperature heat treatment (>2800C) under high strain conditions" (p. 3). This resulting carbon fiber tow was combined with resin by TCR Composites to make prepreg tow. The vectran must be wound onto braiding spools using a winding machine. According to the 2010 vectran website:

> Vectran® is a high-performance multifilament yarn spun from liquid crystal polymer (LCP) ... Pound for pound Vectran® fiber is five times stronger than steel and ten times stronger than aluminum ("Vectran, liquid crystal," 2010).

A Wardwell Horizontal 32-carrier braiding machine is used to braid the vectran jacket around the carbon fiber tow. The process used utilized 8 axial (or longitudinal) vectran strands and 16 braid (or helical) vectran strands triaxially braided around 60K of carbon fiber tow. A take-up system is used to pull the yarn at a constant rate allowing for an even braid jacket. The yarn is collected on a 12-inch wheel called the capstan. This yarn may then be used in the next process.

The second step in the process is braiding the open structure from the pre-fabricated yarn. First, the carbon fiber yarn must be spooled and loaded onto another (larger) composite braiding machine via 16 axial spools and 8 braid spools (for emphasis on bending strength). Next, a mandrel must be greased with a high drip point grease and wrapped with an inert plastic to prevent the resin from adhering to the surface in the curing process. Traverse and braiding speeds must be set on the machine for the desired pitch of the open structure braid. To summarize what our team manager, Casey Sloan, said, "We found that a speed ratio of 3:2 for the braider/traverse worked well for us" (C. Sloan, personal communication, February 22, 2013). One person then operates the machine using the jog button while the other manually applies pressure on the axial yarns and checks to make sure the braid is correctly aligned. Once the whole structure has been braided to the desired length, it is ready to be cured.

The third step in the process is curing the open structures. According to TCR's 2007 resin data sheets, the cure temperature and time for the prepreg in the open structure is 310 degrees Fahrenheit for 1 hour. The mandrel wrapped with the carbon fiber open structure is placed in a large oven in the polymer and fiber building, and the temperature is set accordingly. After one hour the oven is turned off and allowed to cool until the mandrel can be removed, and the open structure is manually pulled off by group members. This is the main process although internal truss yarns can be hand woven in later and cured in the same manner.

Military Lift Senior Design Project Report – Auburn University Team, Spring 2014

Executive Summary

1. Introduction

The Pararescue Jumpers (PJ's) of the United States Air Force are a group of elite Special Operations servicemen who provide medical treatment and rescue operation for personnel in highly inaccessible or contested regions by infiltrating using a parachute. During their mission, the PJ's often have a need to lift and secure heavy obstacles of different sizes and shapes for the extrication of personnel. Due to the surrounding environment and nature of their deployment, the amount of gear the PJ's can carry is severely limited. Therefore, developing a compact and versatile lifting system that can hoist heavy load is essential in the success of PJ's humanitarian or combat operations.

2. Old Design

The previous design from last semester consisted of telescoping cylinders made of carbon fiber material. The cylinders would be pressurized internally with air at 2000 psi and lift the object. This idea was rejected due to the incredibly high psi and the lack of support and agreement from end users and challenge personnel.

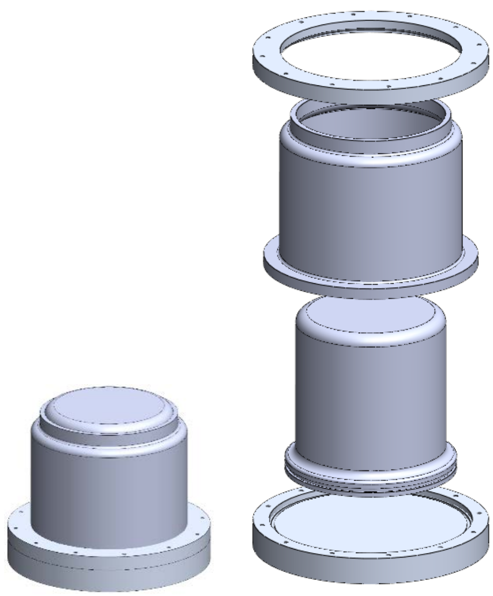


Figure 1: Old Design Illustration

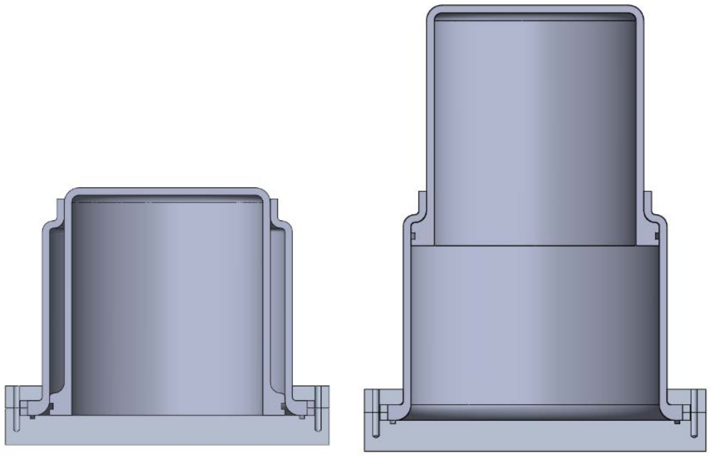


Figure 2: Old Design Cross Section

3. Final Design Overview

The final design consists of a rectangular inflatable bag powered by compressed air stored in a high pressure canister and delivered through a series of valves and hose.

4. Basic Concepts and Theory

4.1 Dimension Analysis

The simplest and most effective method of lifting a heavy load was to use pressurized fluid as a means of providing power to lift the load. The energy needed was expressed in terms of weight lifted and lifting height.

$$Work = Force * distance = Weight * lifting\ height = 55{,}000lbs * 20in = 1{,}100{,}000\ in\ lbs \tag{1}$$

The work exerted by a pressurized actuator was defined by its pressure and volume.

$$Work = \int_1^2 Pressure * dVolume \tag{2}$$

The volume of the bag was determined by examining the inflation of a rectangular bag.

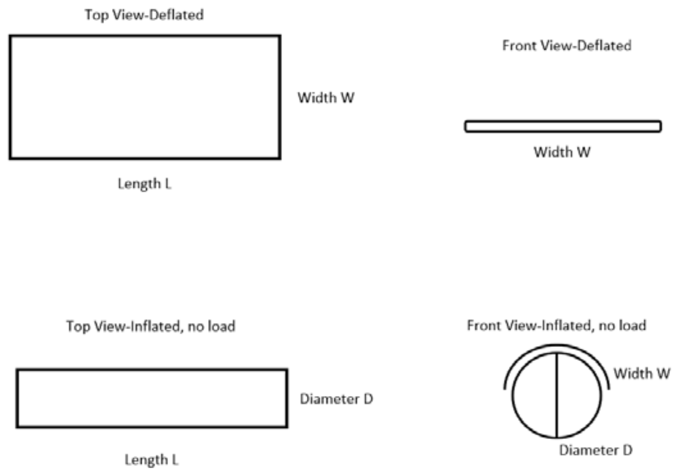


Figure 3: Basic Bag Dimension

The bag was assumed to inflate into a cylindrical shape with no load applied, as shown in Figure 1. The maximum height the bag can be inflated with no load was limited by its diameter. The width W and diameter D were related as $2 * W = \pi D$. Ideally the maximum height the bag can achieve was half its diameter, since at its full inflation height, there would be no surface area to bear the load.

When load was applied, the bag became sandwiched, as shown in Figure 2. The sides of the bag were assumed to inflate into perfect half circles.

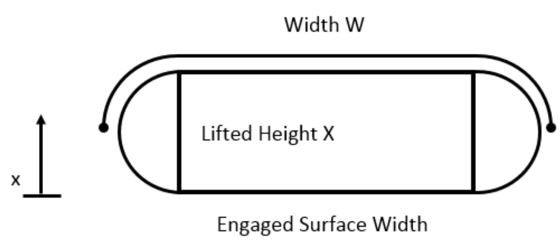


Figure 4: Loaded Bag Dimensions

The dimensions of the surface that remained in contact with the load and the ground was less than the actual dimensions of the bag due to its inflating characteristics. The reduced dimension, or the engaged surface width (ESW) was determined by subtracting the quarter of circumferences of the side circles from the overall width using the lifted height x.

$$ESW = W - 2 * \left(\frac{\pi x}{4}\right) = W - \frac{\pi x}{2} \tag{3}$$

The reduction in length was be modeled similarly.

$$ESL = L - 2 * \left(\frac{\pi x}{4}\right) = W - \frac{\pi x}{2} \tag{4}$$

Using the ESW and ESL, the surface area of the bag that is in contact with the lifting object, or the engaged surface area (ESA), was calculated.

$$ESA = ESL * ESW = \left(L - \frac{\pi x}{2}\right) * \left(W - \frac{\pi x}{2}\right) \tag{5}$$

Using the bag's operating pressure and the surface area, the load supported by the bag as it inflates was expressed as a function of its height.

$$Load = Pressure * Area = P_{bag} * ESA = P_{bag} * \left(L - \frac{\pi x}{2}\right) * \left(W - \frac{\pi x}{2}\right) \tag{6}$$

The general trend showed that as the bag was inflated, the engaged surface area became smaller, and the bag lost its lifting capacity. The maximum lifting capacity of the bag was determined to be at its maximum designated height of half its diameter.

$$Maximum\ Lifting\ Capacity = P_{bag} * \left(L - \frac{\pi(0.5D)}{2}\right) * \left(W - \frac{\pi(0.5D)}{2}\right) \tag{7}$$

4.2 Work Analysis

Assuming the applied load was constant, the load equation could be manipulated to yield an expression for the pressure inside the bag.

$$P_{bag} = \frac{Load}{L * \left(W - \frac{\pi x}{2}\right)} \tag{8}$$

The volume of the bag as it inflates was modeled using the ESW and the ESL. The volume was calculated to be the sum of the volume under the engaged surface and the volume of the outer half cylinders, as shown in Figure 3.

$$\begin{aligned} Volume &= Cross\ Sectional\ Area * Length \\ &= (Area\ of\ half\ circles + Area\ of\ rectangle) * length \\ &= \left[\left(\frac{x}{2}\right)^2 \pi + ESW * x\right] * L \end{aligned} \tag{9}$$

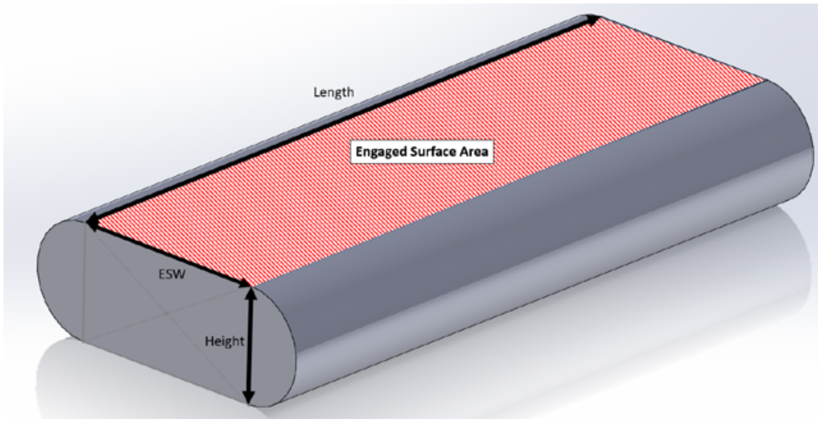


Figure 5: 3-D Illustration of Dimensions

The expression for dV was derived from equation (9).

$$V = \left[\left(\frac{x}{2}\right)^2 \pi + ESW * x\right] * L = \left[\left(\frac{x}{2}\right)^2 \pi + \left(W - \frac{\pi x}{2}\right) * x\right] * L = \left(\frac{x^2 \pi}{4} + Wx - \frac{x^2 \pi}{2}\right) L$$
$$= \left(Wx - \frac{\pi x^2}{4}\right) L \tag{10}$$
$$dV = \left(W - \frac{\pi x}{2}\right) L\, dx$$

Using the derived formula for pressure and volume, equations (8) and (10), into the work equation, the result showed that the work needed to lift the load was simply the product of load and its displacement in vertical, as expected.

$$Work = \int_1^2 P_{bag} * dV$$
$$= \int_{x_1}^{x_2} \frac{Load}{L * \left(W - \frac{\pi x}{2}\right)} * \left(W - \frac{\pi x}{2}\right) * L\, dx = \int_{x_1}^{x_2} Load\, dx = Load * (x_2 - x_1) \tag{11}$$

The work done by a single bag was the product of its operating pressure and its final volume at its maximum designated height. The number of total inflations required by each bag was then calculated using the total required work defined by the problem parameters (desired height of 20 inches for a 55,000 lb load).

$$Number\ of\ Inflations\ Required = \frac{Total\ Work}{Work\ per\ Inflation} \tag{12}$$

4.5 Power Source Analysis

The energy required to lift the load was expressed in terms of the pressure and volume of the lifting bag. The lifting bag's energy capacity was limited by its power source, the high pressure canister. Therefore, the number of lifts N available for a system per canister was calculated using the pressure and volume of

the canister and the bag. The (N+1) term accounts for the requirement that pressure inside the canister must be greater than the pressure inside the bag to drive the airflow.

$$P_{canister}V_{canister} = (N+1) * (P_{bag}V_{bag})$$
$$N = \frac{P_{canister}V_{canister}}{P_{bag}V_{bag}} - 1 \tag{13}$$

Using the number of inflations required per bag, the total number of canisters required for each bag design was calculated.

$$Number\ of\ \ Canister\ Required = \frac{Number\ of\ Inflations\ Required}{Number\ of\ Inflations\ per\ Canister} \tag{14}$$

4.4 Hoop Stress Analysis

The hoop stress equation was used to calculate the stress on the bag. For material with small thickness, the material strength was best expressed in terms of force per unit width. As the radial stress was always greater than the axial stress, the radial stress was used as basis for comparison. By multiplying both sides of the standard hoop stress equation by the thickness term, the material strength could be expressed in units of force per unit length. The radius was estimated as the half the lifting height, using the perfect half circle sides of the bag as the basis.

$$\sigma = \frac{Pr}{t}$$
$$\sigma t = Pr \tag{15}$$

<u>5. Material Information</u>

5.1 Scrim

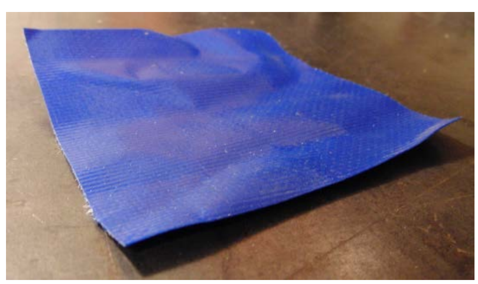


Figure 6: Picture of Scrim

Scrim is a material that is used in the manufacturing of whitewater rafts. This material is a flexible PVC plastic impregnated into a weave. Scrim was chosen because it is a good material to use against abrasion and puncturing. The 15” diameter tube of 33” length cost $80. The scrim tubes that were ordered were heat sealed by an RF sealer. Tensile testing of the heat sealed seams showed material strength of 200 lb/in which as strong as the material itself.

5.2 Kevlar Sleeve information

Figure 7: Picture of Kevlar Sleeve

Kelvar is manufactured fiber spun from a liquid crystal polymer (LCP). A braided aramid Kevlar sleeve was used to cover the scrim bags. The type of Kevlar used for the construction was named A&P Kevlar sleev, selected based on its lightweight construction, strength of material, and abrasion resistance. The Kevlar sleeve weighed one pound for every 3.3 feet and had a burst pressure of 342 psi.

5.3 Vectran Cloth

Figure 8: Picture of Vectran Cloth

Vectran is also manufactured fiber spun from an LCP and braided into cloths or sleeves. The material selection was based on its high tensile strength and abrasion resistance.
Tensile testing data that showed that the vectran held up to a force of 213.6 lbs. / in, CITE this the maximum force that the tensile testing machine could produce. Vectran is the most expensive out of all the materials at a cost that is estimated to be \$109.00 $per\ yard^2$.

The vectran cloth used for this application had a thin coating of polyurethane on the inner surface to ensure air seal.

Several experimental manufacturing techniques were used to find the best vectran seams. One of the techniques was a heat and pressure sealing. Average shear force to break the heat seal was found to be 200 lbs. / in.

3M 5200 glue was an adhesive used to form seams. This material was found to stick to only the cloth side of the vectran. When glued to the polyurethane side, the 3M 5200 glue would peal the polyurethane off of the vectran cloth causing a very small air leak that lead to failure.

New section for glue and treatment??

5.4 Sleeve

Figure 9: Picture of Vectran Sleeve

The 400d Vectran® from Lamcotec was another variety of vectran used. This material did not have polyurethane coating to serve as air seal. sleeve was the largest of the sleeves used. Don't introduce word sleeve yet, we can to that at the proposed prototype section. The 400d Vectran® Lamcotec had tensile strength of 534 lbs/in and elongation of 8% **Information was from Beales work Cite** Like the other variety of Vectran, the sleeve has great abrasion resistance.

The seams of the sleeve are sew together with Kevlar. Three passes were made on the first prototypes seams and only 2 passes were used on the second prototypes seams. Out of place?

5.5 Liquid Polyurethane

Bondaid

Liquid polyurethane were used to serve as

5.6 Glues

Figure 10: 3M 5200 Glue

3M 5200 glue is a high performance polyurethane glue. Originally developed for marine use, the seal retains its strength and stays flexible to allow for structural movement and absorbs stress caused by movement. 3M 5200 adhered best to the cloth side of vectran, but showed poor adhesion on the polyurethane and scrim material.

Figure 11: Loctite Vinyl and Rubber Adhesive

Loctite Vinyl and Rubber Adhesive is an adhesive that is highly flexible to withstand bending and torsion, keeping the bond intact. Loctite adhered better to the scrim material but performed poorly on Vectran.

<u>6. Proposed Designs</u>

Three different designs were proposed for the consideration of the final product. The three proposed solutions were designated as follows.

1. Kevlar Sock Scrim
2. Vectran Sock Scrim
3. Vectran Only

Both solutions one and two shared the idea of inserting a weaker material, scrim, inside a stronger material, either Kevlar or Vectran. The weaker material serves as the airtight inner bladder, while the stronger yet porous sock material serves as the outer reinforcement to hold the pressure.

First, the inner bladder was constructed and tested for air tightness and material failure. The scrim proved to contain the air well, however, the bursting pressure for the scrim only bag were observed at 50 psi.

The Kevlar sock scrim bag was constructed by inserting the scrim inner bladder into a standard Kevlar sock. The Kevlar and the bag were sized so the inner bladder fit tightly inside once inflated. The Vectran sock scrim bag was constructed in a similar fashion. The Vectran bag, however, was sized bigger due to the larger size of the available Vectran sock. The Vectran only bag was constructed entirely of Vectran, without any reinforcing outer layer.

6.1 Kevlar Sock Scrim Bag

One lifting bag system was made out of scrim. The bags were constructed using 15” x 36” scrim material formed into a hollow cylinder by a two inch heat sealed seam running lengthwise down the bag. The horizontal seams were made using Loctite glue (referenced in the Materials section). These bags were then covered in a braided Kevlar sleeve to decrease hoop stress and contain the corners of the material (the likeliest source of failure). Below are the manufacturing steps used to create these bags.

Loctite glue was placed inside the bag, in-between the two opening flaps. It was spread evenly from the edges to approximately 2” down. The two flaps were then pressed together and sealed. Figure 12 shows the glued seam.

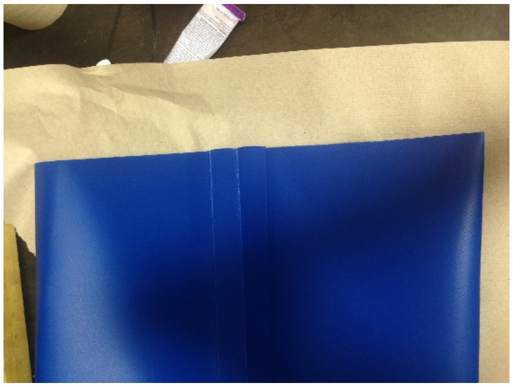


Figure 12

A 1” overlap was then made using the glued seam and laid over on itself. The corners were then pressed in to eliminate harsh edges and glue was spread on the entire length of the overlap and in to the corners. The overlap was then pressed down and secured to the bag. Figure 13 shows the overlap and corners after gluing, before securing.

Figure 13

Approximately 4” of scrim was then cut to create a “patch” over the overlap. This was made to reinforce any weak seals in the overlap and corners. Glue was spread evenly over the entire length of the patch and pressed on to the bag, shown in Figure 14 (Note: the black and blue color make no difference, with the black only being undyed material). The material was then clamped together using two pieces of 2x4 to evenly distribute the force, as shown in Figure 15. This seam was left to set for at least 24 hours.

Figure 14

Figure 15

Before the same seam is made on the other side, a hole is cut for the valve placement. Another piece of scrim was cut and glued to reinforce the area around the valve hole, as the discontinuity would serve as a stress concentration point, shown in Figure 16. Afterwards, the valve was inserted in the bag and tightened down with wrenches (See Air Supply System for valve information). Figure 17 shows the valve inserted in to the bag. Steps 1-3 are then repeated on the opposite side of the bag.

Figure 16

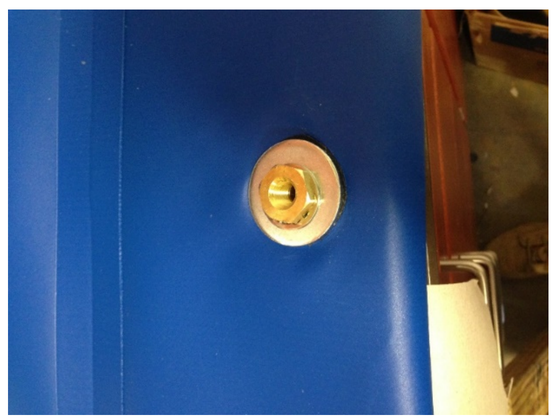


Figure 17

Each corner of the bag was then dipped in to a bucket of liquid polyurethane (discussed in Materials section) to completely seal the corners and prevent any potential air leaks, as shown in Figure 18.

Figure 18

The Kevlar sleeve was then rolled out to the approximate length of the bag, shown in Figure 19, and then parted off. The bag was then inserted in to the sleeve and a single bead of 3M glue was laid down to seal the sleeve together and prevent fraying. Figure 20 and 21 on next pageshows the final completed bag, without and with its Kevlar sleeve.

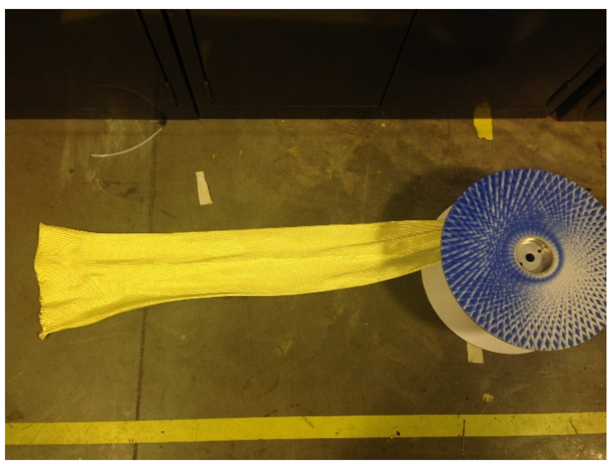


Figure 19

Figure 20

Figure 21

6.2 Vectran Sock Scrim Bag

For this design a Baraboo scrim tube was again used with original dimensions of 24” diameter by 3’ long. It was then folded and seamed up and glued the same as the Baraboo bags previously mentioned. Once constructed into a bag the dimensions were roughly 35” wide by 30” long.

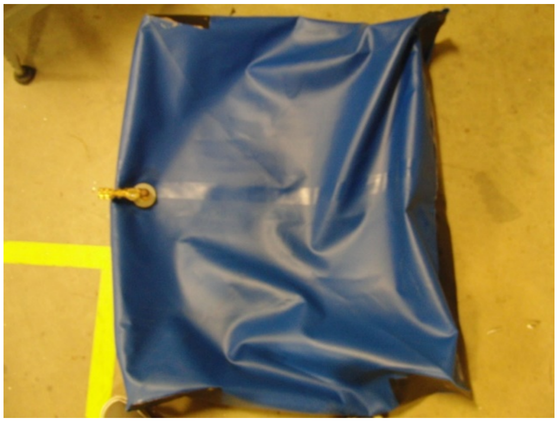


Figure 22

Then using the Vectran sleeve material, the bags were placed inside and inflated to approximate full inflations.

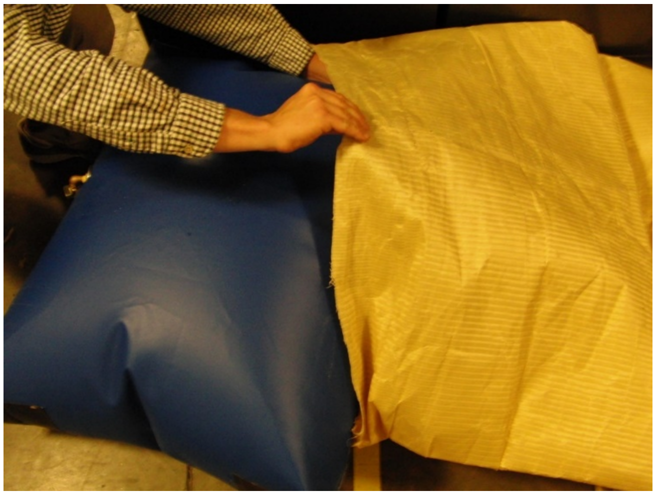


Figure 23

The sleeve was then pulled up to the centerline of the bag and marked. Next, the excess sleeving was cut off and the ends of it rolled up against the bag to provide an area to sew on. Then using Kevlar thread, three seams were sewed on the sleeve to close off one end.

Figure 24

Figure 25

This process was repeated on the other side.

6.3 Vectran Only Bag

Because of its extreme strength, flexibility, light weight, and abrasion resistance, Vectran was selected as an ideal candidate for inflatable bag material. The Vectran was coated on one side with polyurethane to ensure an air-tight material. The 3M 5200 glue was used to create all of the seams in the bag. The marriage of these two materials along with creative bag geometry resulted in air bags that inflated to large sizes but could be rolled up quite small and stored with ease.

Two sizes of bags were developed. The construction method was identical, and only their dimensions were different. The larger bag is twice the size of the smaller one. Figs. 26 and 27 display the large and small bags inflated, respectively, and Figs. 28 and 29 show them deflated and rolled up for storage. All of these figures have a tape measure extended to 1’ for scale. The bags inflate to a round shape, so the off-centered weight of the valve causes them to roll up on their side.


Figure 26


Figure 27


Figure 28


Figure 29

The large bag was sprayed with Rust-Oleum Leakseal flexible rubber spray, giving its black color. The spray was applied in an attempt to protect the vectran against UV light (which causes degradation of the material) and to add abrasion resistance. The benefits from the coating proved negligible, and moreover, it had the adverse effect of causing debris to adhere to the bag in an unclean environment. Therefore, the spray was abandoned in the production of the small bags. Both models are outfitted with quick-release hose connectors and a ball valve to allow for control of internal pressure.

Figs. 5-8 demonstrate the creative seam techniques developed to maximize the strength of the 3M 5200 adhesive and cause the bag to take a rounder shape and eliminate corners. Even though the glue had poor adhesion characteristics on the inner polyurethane layer, the adhesive properties on the cloth layer proved satisfactory. Therefore, the glue was applied to the cloth surface exclusively. Any seam that necessitated cloth on polyurethane gluing was reinforced with additional strip to overcome the poor polyurethane adhesion.

Another challenge in constructing the bag was in providing a method to distribute the stress in the bag's rectangular corners. The illustrated gluing method was developed to eliminate the corner and give the bag a better inflated shape.
Also, peeling causes the glue to fail quickly because all of the force is concentrated on the area nearest the joint. (unclear?) These seams eliminate peeling and minimize corners. (Fig. 8 was taken after testing in an unclean environment).

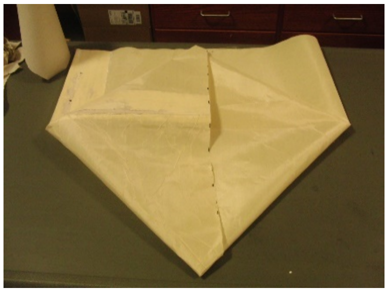


Figure 30

Figure 31

Figure 32

Figure 33

Table 1 shows the final performance results of these two bags.

Table 1

	Large Bag	Small Bag
Total Lifting Surface Area	540 in cu.	324 in cu.
Maximum Pressure	60 psi	60 psi
Factor of Safety	2	2
Lifting Height	15 in	12 in
Load Capability	32400 lbs	19440 lbs

Better table is available below. Compare and decide.

This design is not without flaws. The material occasionally develops pinhole leaks that do not inhibit initial lifting much, but they do mean that the bag loses pressure over time. Also, leaks can develop around the seams on occasion. The pinhole leaks can be found with soap-water and patched with a square of vectran and good glue coverage. The leaks around the seams can also be fixed with a liberal application of the glue. Finally, at pressure, the bag is prone to puncture on sharp objects if not deployed carefully. This can be avoided by a brief inspection of the surface to be lifted and placing the bag so that sharp edges are avoided. It should be noted that contact with rounded edges does not compromise the bags. This can be added in the review, not the construction section.

7. Power Source

For the power source, a 90 in^3 4500 PSI Ninja Paintball air tank is used. The tank is made of carbon fiber and uses compressed air for inflation. The tank is 12” x 4.5” and weighs 3.3lbs unfilled. It houses a built-in air regulator that regulates pressure down to approximately 800 PSI. A 6000 PSI gauge on the regulator shows the pressure currently in the tank. The tank is easily filled through a 1/8” NPT quick disconnect on the side of the regulator. Paintball air tanks allow for easy refill and a very low output response curve. They also allow for a larger pressure per volume of the container. Scuba tanks of similar pressure are typically larger and heavier than the current system. Carbon fiber also adds toughness and ruggedness to the system as opposed to steel or aluminum tank material. Weight and power output were chosen as priority conditions over size. If size adjustments to the system need to be made, smaller volume air tanks can be used universally. Multiple tanks will be needed, however, to achieve the same air capacity as the current solution.

Other power sources were considered before the final source was chosen. A chemical source using sodium azide, the chemical used in automobile airbags, was researched. It is a highly reactive, rapidly expanding chemical chosen for its quick inflation time. The chemical, however, is extremely volatile and

potentially dangerous. Exposure to the chemical can cause brain and heart damage. Due to the chance of bag failure under load, the risk of exposer to operators is increased exponentially compared to the traditional systems. This led to the eventual rejection of a chemical system. A gas-powered air compressor was briefly considered but was rejected due to the added weight, bulk, and noise generation. Gas also becomes more unstable under extreme conditions potentially found in some rescue missions.

8. Power System

A system of regulators move air from the high pressure tanks to the maximum allowable output of 60 PSI. The 4500 PSI tank pressure is regulated to approximately 800 PSI using the attached Ninja Paintball regulator. An easy on/off air source adaptor (ASA) is connected to the top of the regulator. A latch flips down to turn on the air supply and up to quickly turn it off. A steel braided 1/8" NPT high pressure macroline runs from the ASA to an inline regulator. This regulates the air pressure down to approximately 60 PSI. The pressure can be easily regulated using a ¼" hex wrench (included in the system with an attached knob). The air then passes through a one-way check valve that prevents back pressure from flowing back in to the tank. This is then attached to a steel ¼" NPT 4-way connection. Attached to the connection is a 160 PSI gauge, which allows the operator to monitor the air leaving the inline regulator moving in to the bag, and an air release valve. The air release valve is a handled ball valve that allows for the easy purging of the remaining air in the hose line and built-up pressure in the bag. This allows for the operator to safety depressurize the system without endangering themselves by getting close to the pressurized bag under load. Air then moves through a 10' 500 PSI high pressure hose line to a ¼" NPT quick connect valve. The diagram and picture of this system is shown in Figures 34 and 35.

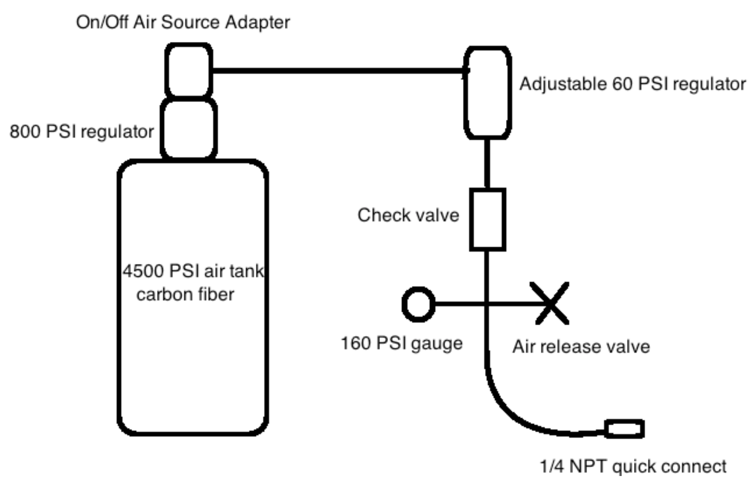


Figure 34

Figure 35

The quick connect is attached to a two-part valve system found on the lifting bags. A 1 1/8" through-wall assembly is attached directly to the bag. Between two nuts is a lock washer, steel washer, the bag, a rubber gasket, and another steel washer. The diagram and picture of the through-wall assembly are shown in Figures 36 and 37.

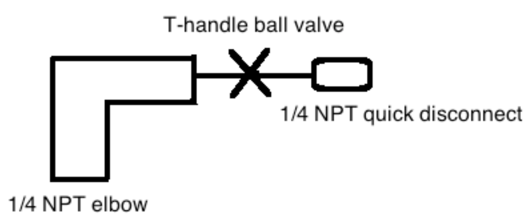


Figure 36

Figure 37

Connected to the through-wall is the valve assembly. A ¼" NPT elbow is attached to a T-handle ball valve. This allows for the easy on/off of air flow in and out of the bag. A ¼" NPT quick disconnect is then connected, that fits directly to the hose. This assembly is shown below in Figures 38 and 39.

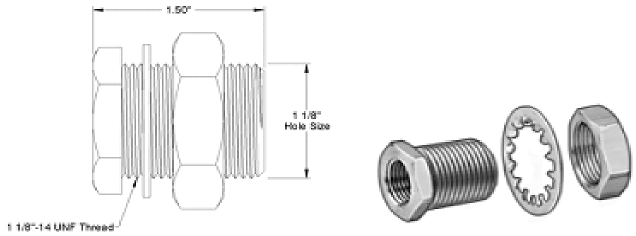


Figure 38

Figure 39

9. Bag Comparison

The analysis detailed in the calculations were performed on each of the bag designed and tabulated below.

Bags	Dimensions		Material	
	Length (in)	Width (in)	Material Strength (lbs/in)	Hoop Stress (lbs/in)
Kevlar Sock Scrim	33	15	200	70.5
Vectran Sock Scrim	34	30	200	142.5
Vectran Only Large	50	27	133.5	127.5
Vectran Only Small	27	25	133.5	118.5

Bags	Lifting Capacity		
	Max. Lift height (in)	Volume at Max. Height (in^3)	Load per Lift (lbs)
Kevlar Sock Scrim	4.7	824	5854
Vectran Sock Scrim	9.5	2923	8630
Vectran Only Large	8.5	3520	15,000
Vectran Only Small	7.9	1663	5511

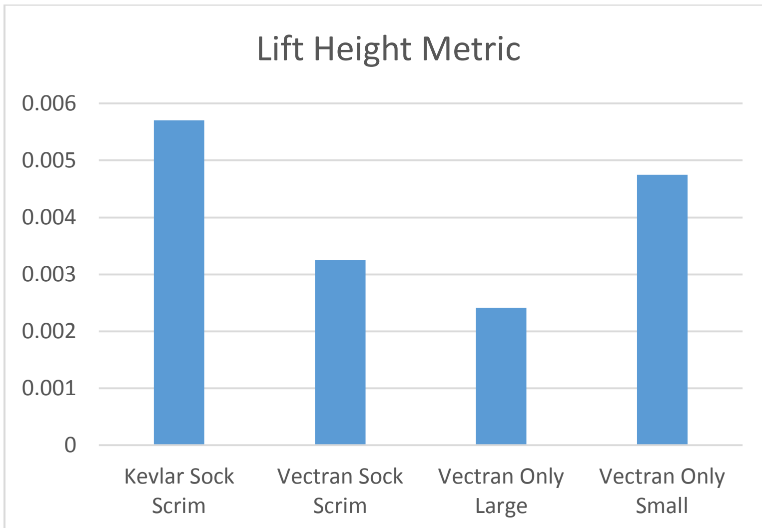
Bags	Energy Analysis		
	Work done per lift (lb in)	Total Work Required (lb in)	Number of Lifts Required
Kevlar Sock Scrim	27,513	1,100,000	40
Vectran Sock Scrim	81,985	1,100,000	14
Vectran Only Large	127,500	1,100,000	9
Vectran Only Small	43,536	1,100,000	26

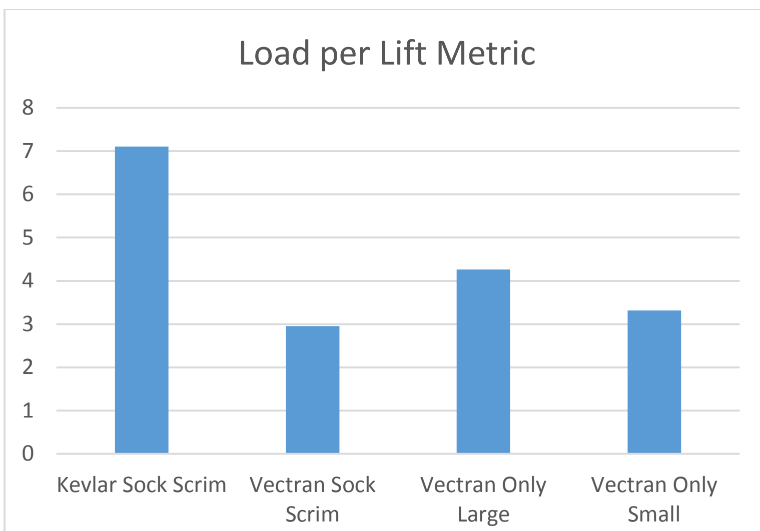
Bags	Power Source	
	No. of Inflations per Canister	No of Canisters (#)
Kevlar Sock Scrim	15	3
Vectran Sock Scrim	3.5	4
Vectran Only Large	2.8	4
Vectran Only Small	7	4

Because each bag had different dimensions, a direct comparison among them could not be made. Therefore, two metrics of performance were developed for comparison. The volume at maximum inflated height was considered the “cost” of inflating each bag, and the maximum lift height and the load per lift were considered “profit” from using the bag. A ratio of profit to cost can be used to gauge the performance of each bag.

$$
\begin{aligned}
Performance\ Metric &= \frac{profit}{cost} \\
Lift\ Height\ Metric &= \frac{Max.Lift\ height}{Volume\ at\ Max.Height} \\
Load\ per\ Lift\ Metric &= \frac{Load}{Volume\ at\ Max.Height}
\end{aligned} \quad (7)
$$

The results of comparison are shown in figures





<u>Final Design</u>

Heavy detail, include images.

Or we can just say what we picked and give reasons.

Evolution of the seams

10. Further Improvements

10.1 Heat and Compression Sealed Vectran

The process for determining the best method for heat sealing Vectran required a lot of trial and error. Two types of Vectran were experimented with. One had a film of polyurethane on both sides of thick fibers. The other type had a film on one side of a thinner fibers. A compression molding machine was used to determine the most effective method for sealing the material.

The variables that affect the integrity of the seal include:

- Temperature
- Pressure
- Time
- Materials in contact

A ladder study was performed by altering the variables and testing the bond in a tensile testing machine. The study showed that a urethane to urethane bond on the thicker material resulted in the strongest seal. The optimal temperature, pressure, and time combination was 163ºC at 3 tons for 100 seconds.
Figure: Compression Molding Machine

During manufacturing, some of the urethane was unintentionally bonded together. This caused the film to peel off one side of the material when it was inflated. The exposed fabric allowed for pinhole leaks to form in the bag. This problem was solved by applying more urethane to the fabric.